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**Airborne Observations of
Biomass Fires**

AIRBORNE OBSERVATIONS OF BIOMASS FIRES

University of Washington's Contributions to the
Draft Report March 6-7, 1990

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Final Report to the
National Institute of Standards and Technology

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PREFACE

This final report has been prepared as components and sections to a much larger multidisciplinary study which focuses on the Hill Township biomass test fire in Ontario Province, Canada on August 10, 1989. The report is paginated to facilitate its incorporation into the larger report. However, this report can be sensibly read in the order presented and provides a detailed summary of the various biomass test fires the University of Washington's team has studied under the auspices of the Defense Nuclear Agency.

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INTRODUCTION

The University of Washington's Convair C-131A (Fig. i-1) has been used successfully to observe the smoke plumes and severe weather resulting from the Hill and Wicksteed (Figs. i-2 and i-3 respectively) prescribed burns in Ontario, Canada. These fires are milestones in our biomass fire research. Here we first employed our dual wavelength lidar, we achieved several multiple method estimates of cloud and precipitation scavenging efficiencies and we successfully operated the AVQ-17 forward looking infrared (FLIR) sensor to penetrate the smoke pall and directly view fire and flame phenomena. These lidar and FLIR measurements and other recent fire and volcano observations have demonstrated the utility and importance of airborne remote sensing techniques as the phenomena scale grows. Indeed these Canadian prescribed burns were a challenge both in scale and duration. The fire convective scale increased the time the aircraft needed to move from one sample location to another, the air motion turbulence challenged our instrumentation (the calibration of one instrument seems to have varied erratically with each heavy bump, and the lidar repeatedly turned itself off on negative g encounters), and finally, the growth of the Hill fire into a thunderstorm evoked some careful attention to flight safety.

Nevertheless, these two fires are developing into a valuable and growing data resource. Because the airborne perspective of these fires is in many ways different and in

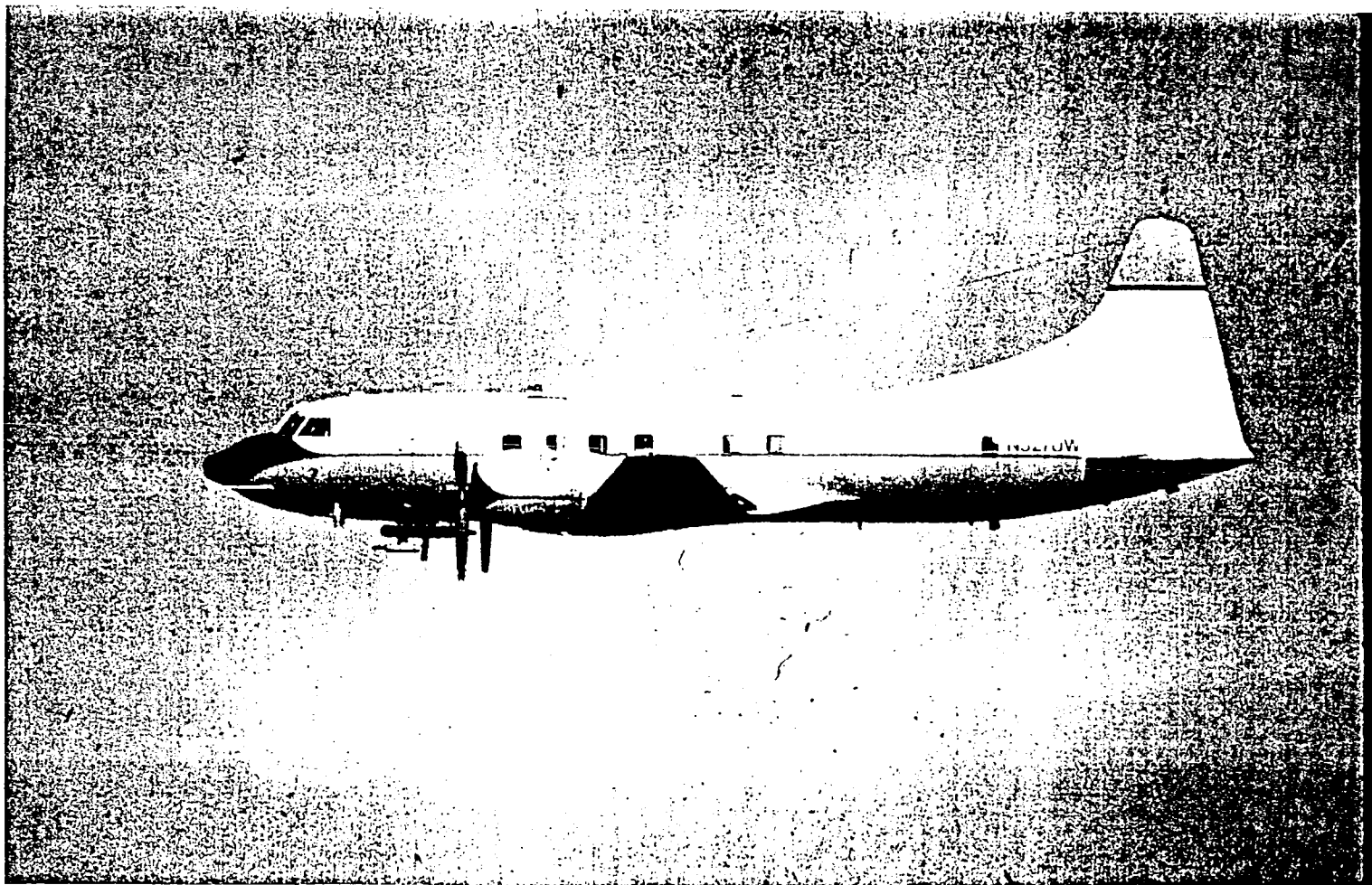


Figure i-1 University Of Washington's Convair C-131A research aircraft.

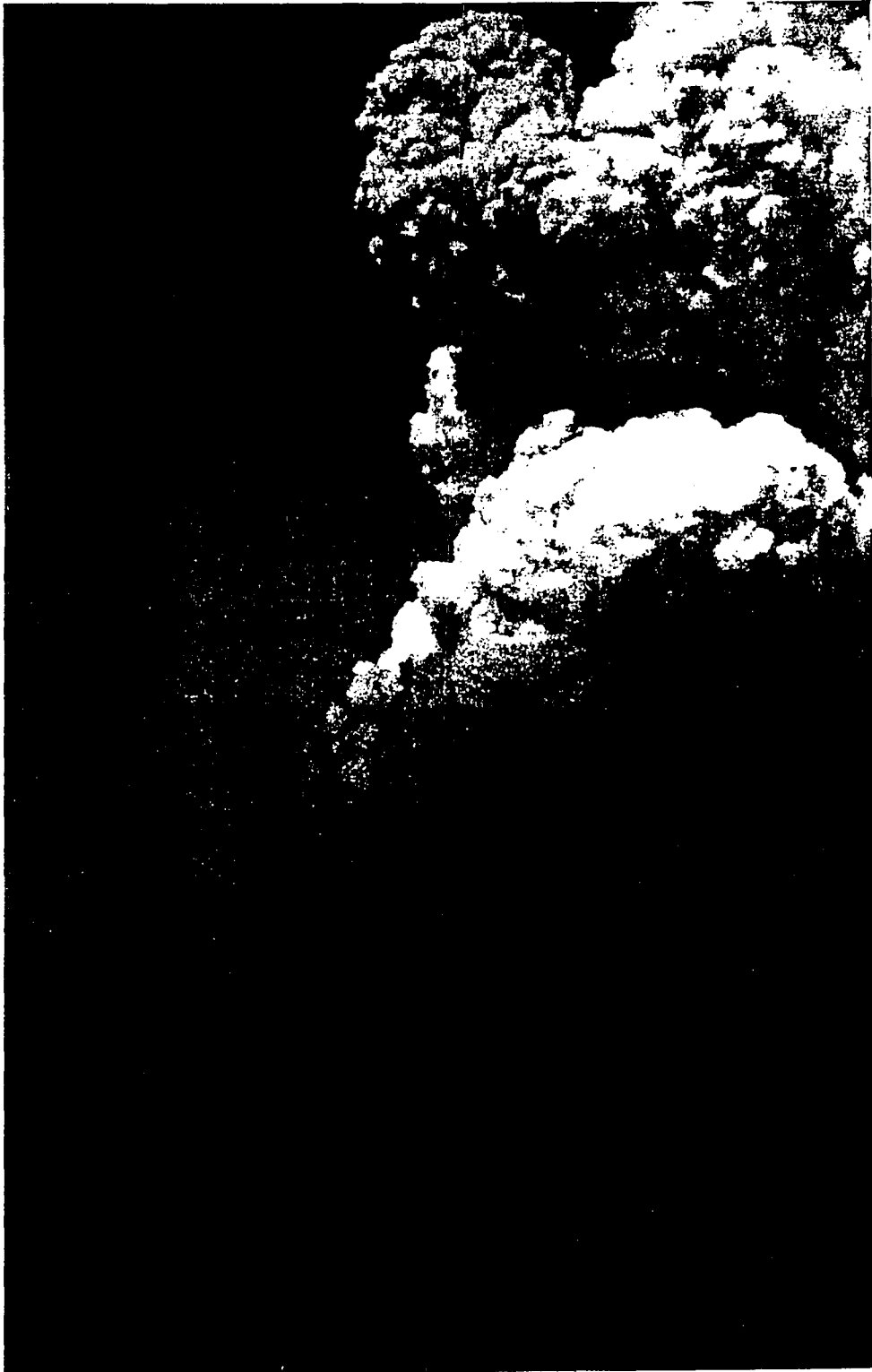


Figure i-2 Photograph of the smoke pall and capping cumulus cloud at the Hill fire.



Figure i-3 Photograph of fire-spawned cumulus cloud at the Wicksteed fire.

some ways unique, the 1989 data has been integrated into our total data set of seventeen biomass fires although the current work is highlighted. Much of our work on the earlier fires in this data set has already been published (Radke *et al.*, 1988), and a paper on trace gas emissions from some of these fires is currently in press (Hegg *et al.*, in press). We therefore often quote extensively from these two papers without reference when discussing data which was obtained prior to 1989. Information on all seventeen biomass fires, plus a series of aviation fuel (JP-4) fires, is summarized in Table i-I. Fourteen of the fires were prescribed burns, and two were portions of major wild fires on the Oregon-California border that burned largely uncontrolled for over a month in the late summer of 1987.

AIRBORNE INSTRUMENTATION AND PROCEDURES

The measurements were made aboard the University of Washington's C-131A research aircraft. This twin-engined, propeller-driven airplane carries instrumentation for measuring the size and nature of aerosol and cloud particles, trace gas concentrations, and meteorological parameters. Major portions of the aerosol system have been described by Radke (1983) and the trace gas instrumentation has been described by Hegg *et al.* (1987). The primary instruments used in this present study are listed in Table i-II. For a comprehensive listing the reader is referred to Appendix A.

The aircraft made horizontal passes either through the ascending smoke column or perpendicular to the axis of the stabilized smoke plume downwind from the fires. "Grab" samples of air for determination of aerosol size distributions were averaged over ~0.5 km of flight path, and those for carbonaceous trace gases and aerosol total mass over ~1 km of flight path.

Measurements of the light-extinction, scattering, and absorption coefficients were obtained from a combination of continuous measurements and grab-bag sampling. Continuous measurements of the extinction and scattering coefficients were obtained with a highly stable 7 m long extinction cell and an integrating nephelometer (Weiss and Radke,

Table i-I

FIRES EXAMINED IN PRESENT STUDY

Fire	Date	Location	Size (hectare)	Type of Fire	Fuel
Abee	22 Sept 86	Montesano, WA	40	Prescribed	Debris from Douglas Fire & Hemlock
Eagle	3 Dec 86	Ramona, CA	30	Prescribed	Standing Black Sage, Sumac & Chamise
Lodi 1	12 Dec 86	Los Angeles, CA	40	Prescribed	Standing Chaparral, Chamise
Lodi 2	22 June 87	Los Angeles, CA	150	Prescribed	Standing Chaparral, Chamise
Hardiman	28 Aug 87	Chapleau, Ontario	325	Prescribed	Debris from Jack Pine, Standing Aspen and Paper Birch
Wheat	31 Aug 87	Rosalia, WA	~10	Prescribed	Wheat stubble
Myrtle/Fall Creek	2 Sept 87	Roseburg, OR	2,000	Wild Fire	Standing Pine, brush & Douglas Fir
Silver	17-19 Sept 87	Grants Pass, OR	20,000	Wild Fire	Douglas Fire, True Fir and Hemlock
Satsop	19 Sept 87	Satsop, WA	40	Prescribed	Debris from Douglas Fir and Hemlock
Troy	8 Oct 87	Troy, MT	70	Prescribed	Debris from Pine, Douglas Fir and True Fir
Tyndall	15-24 May 88	Tyndall AFB, FL	410 - 729 m ²	Pool	Aviation Fuel (JP-4)
Battersby	12 Aug 88	Timmins, Ontario	718	Prescribed	Jack Pine, White and Black Spruce
Peter Long	22 Aug 88	Timmins, Ontario	217	Prescribed	Jack Pine, White and Black Spruce
Carbonado	27 July 89	Enumclaw, WA	40	Prescribed	Debris from Douglas Fir & Hemlock
Summit	1 Aug 89	Grangeville, ID	100	Wild Fire	
Hill	10 Aug 89	Chapleau, Ontario	486	Prescribed	"Chained" & Herbicidal Paper Birch & Poplar
Hornepayne	12 Aug 89	Hornepayne, Ontario	700	Prescribed	"Chained" & Herbicidal Birch, Poplar & Mixed Hardwoods
Mabel Lake	25 Sept.89	Kelowna, B.C.	29	Prescribed	Debris from Hemlock, Deciduous, Douglas Fir

Table i-II Principal Instrumentation Aboard the University of Washington's C-131A
Research Aircraft Used in this Study

(a) Particle Sizes and Concentrations

Instrument	Equivalent Particle Diameter (μm)
Condensation nucleus counter*	> 0.005
Diffusion battery with condensation nucleus counter†	~ 0.01 - 0.1
Electric aerosol analyzer†	~ 0.01 - 1.0
Active scattering aerosol spectrometer†	0.09 - 3
Laser aerosol spectrometer†	0.5 - 11
Optical particle counter†	2.6 - 48
Forward-scattering spectrometer probe*	3 - 45

(b) Trace Gas Chemistry

Gas	Technique	Detection Limit (ppbv)
SO ₂ *	pulsed fluorescence	> 1
O ₃ *	chemiluminescence (C ₂ H ₄)	> 5
NO, NO ₂ *	chemiluminescence (O ₃)	> 1
CO†	correlation IR spectrometer	> 100
CO ₂ †	IR spectrometer	± 2 ppm
NH ₃ †	impregnated filter	% variable
Whole air grab sample†	GC/mass spectrometer (post flight)	variable

(c) Aerosol Characteristics

Parameter	Instrument	Range
Light-scattering coefficient*	integrating nephelometer	$1 \times 10^{-6} - 2.5 \times 10^{-3} \text{ m}^{-1}$
Light-extinction coefficient*	optical extinction cell	$5 \times 10^{-5} - 10^{-2} \text{ m}^{-1}$
Particle mass†	quartz microbalance impactor	< 2 μm diameter
Bulk aerosol chemistry† (soluble anions concentration)	Teflon filters, ion chromatography	$\left\{ \begin{array}{l} \text{Cl}^- \pm 14\% \\ \text{SO}_4^{2-} \pm 4\% \\ \text{NO}_3^- \pm 11\% \end{array} \right.$
Particle morphology† & chemistry	impaction, electron microscopy	
Carbon soot§†	filtration, light absorption, pyrolysis	

* Continuous measurements.

† Grab sample measurements.

§ Analysis by Radiance Research and Sunset Laboratories.

1987). This technique produces excellent agreement with filter samples analyzed by the integrating plate method (Weiss et al., 1979) and with the elemental carbon analysis of sequenced pyrolysis of the quartz filters.

Further details regarding sampling and analysis methods will be supplied in the sections which follow.

VII C.2 PARTICLE SIZE DISTRIBUTIONS

The particle size distributions, particularly the volume distributions, showed comparatively little variation in shape from one fire to another or during any one fire while near the source, although particle concentrations varied widely. Shown in Figure VII C2.1 are average number and volume distributions measured in the smoke plumes near the sources of three fires. The accumulation mode (0.1-2.0 μm) often dominated both the number and volume distributions and it always contributed overwhelmingly to the light-scattering coefficient. Particles in the accumulation mode consisted primarily of tarry, condensed hydrocarbons, typically spherical in shape, but they also contained some water-soluble inorganics (primarily SO_4^{2-} and NO_3^- ; Hegg *et al.*, 1987). This accounts, in part, for their activity as very efficient cloud condensation nuclei (Radke *et al.*, 1978; Hallet and Hudson, 1989).

The coarse particle mode ($>2 \mu\text{m}$) showed considerable variations. For example in the Lodi 1 fire there was a mode near 10 μm (Fig. VII C2.2) comprised mostly of condensed hydrocarbons with a significant fraction of soil particles (Cofer *et al.*, 1989). In addition to this mode, an examination of the data from our laser hydrometeor cameras shows that ash and debris up to and exceeding 1 mm in diameter are often found in concentrations greater than 10 m^{-3} . While we see significant variations in the amount of this super giant aerosol, it is typical of all the large fires studied. Lofting of soil and ash by intensely burning biomass fires has also been observed by Einfeld *et al.*, (1989).

The nucleation mode ($<0.1 \mu\text{m}$) was the most variable and appears to change in response to differences in the particle number concentration and the age of the smoke. Figures VII C2.3 and VII C2.4 each show particle number and volume distributions taken from samples of greatly differing total number concentrations during the Battersby and Hill fires, respectively. In both figures the distributions with lower concentrations (curve A) were obtained from column samples taken below cloud base less than 30 minutes after

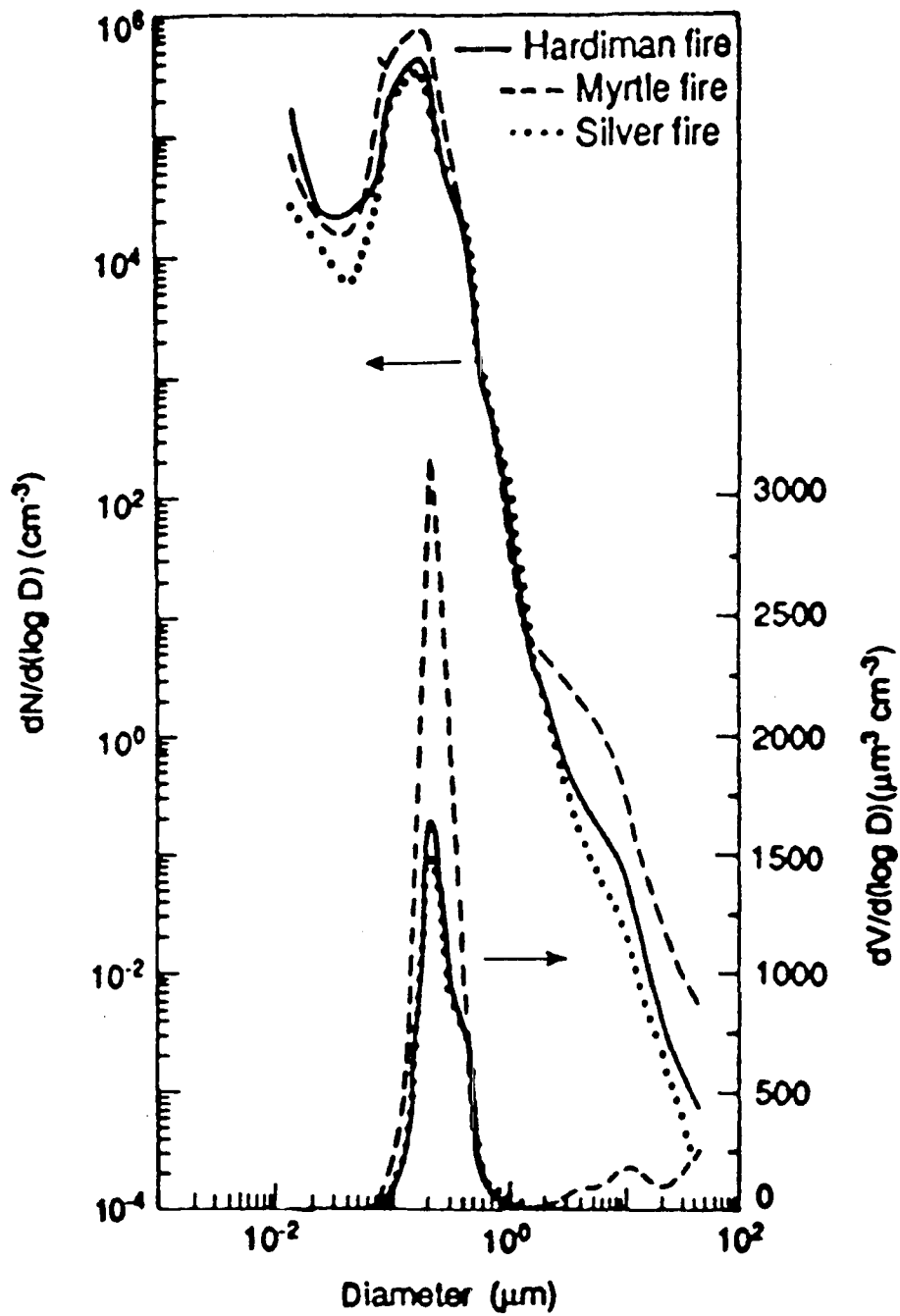


Figure VII C2.1 Mean number and volume distributions of particles measured in the smoke plumes near the sources of three fires.

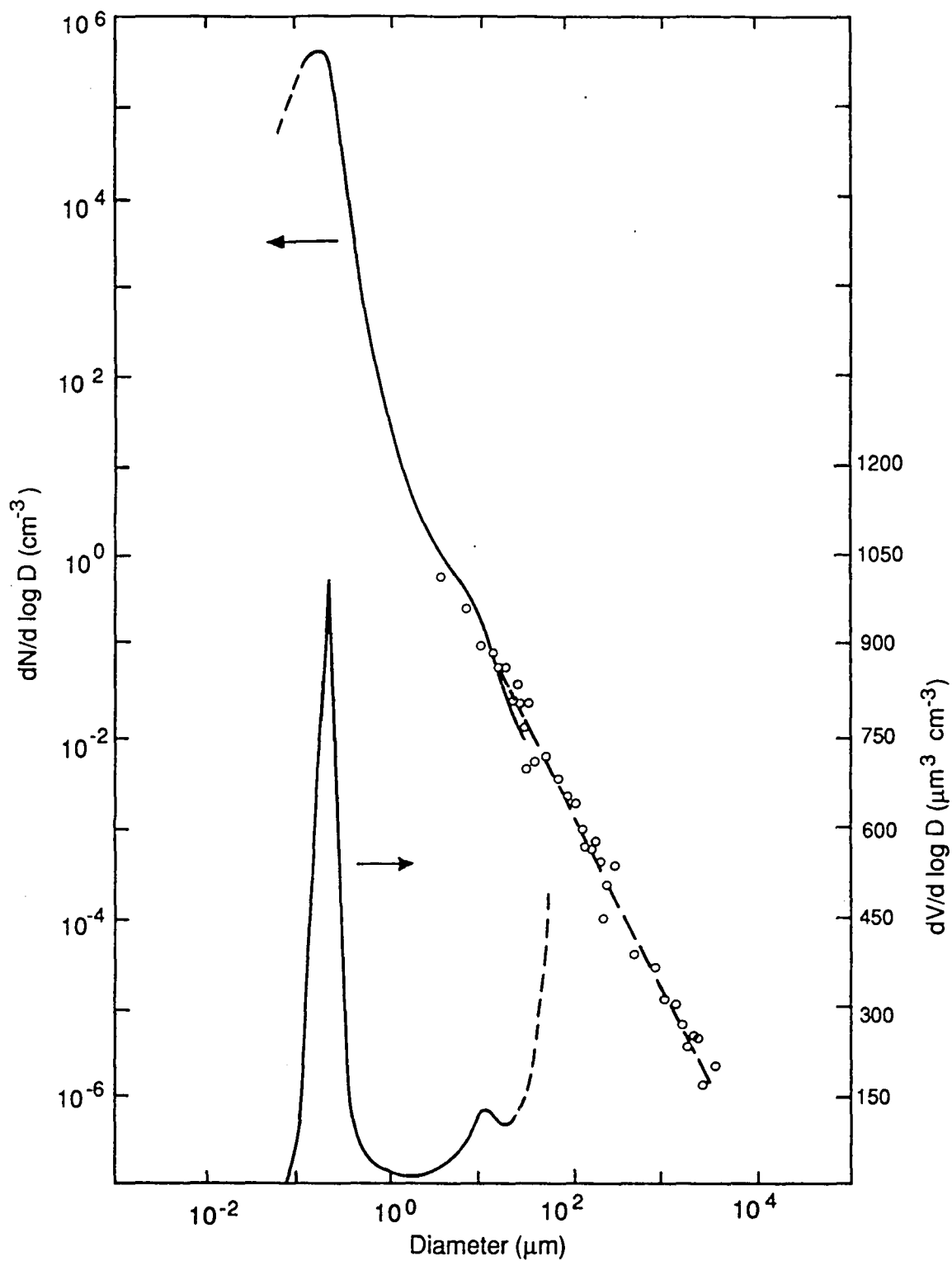


Figure VII C2.2 Mean number and volume distributions of particles measured in the ascending column at the Lodi I fire. Data points representing large, giant, and ultra-giant particles were obtained from laser hydrometeor cameras.

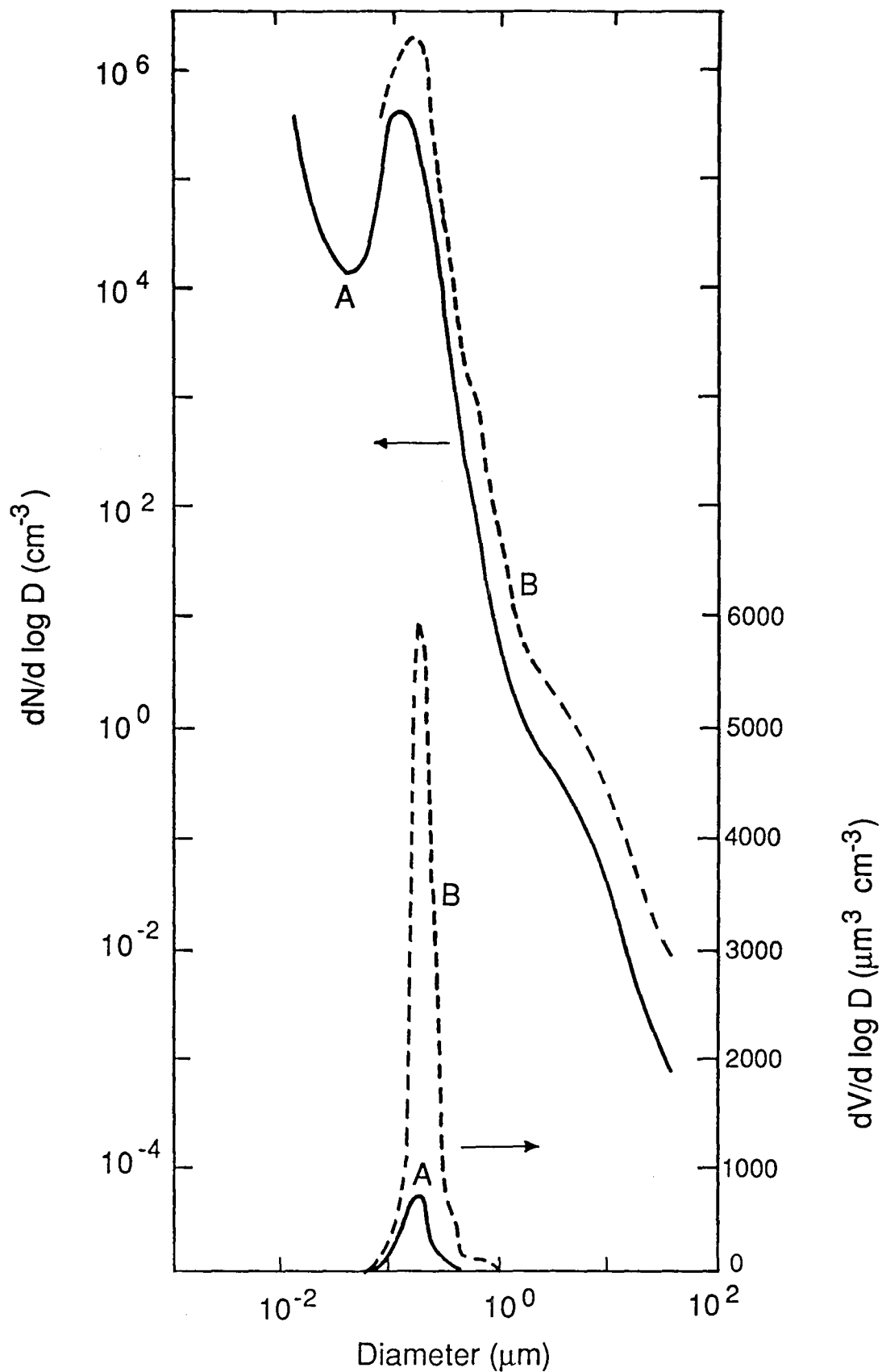


Figure VII C2.3 Mean particle number and volume spectra measured in two flaming phase column samples (A) and four smoldering phase column samples (B) at the Battersby fire.

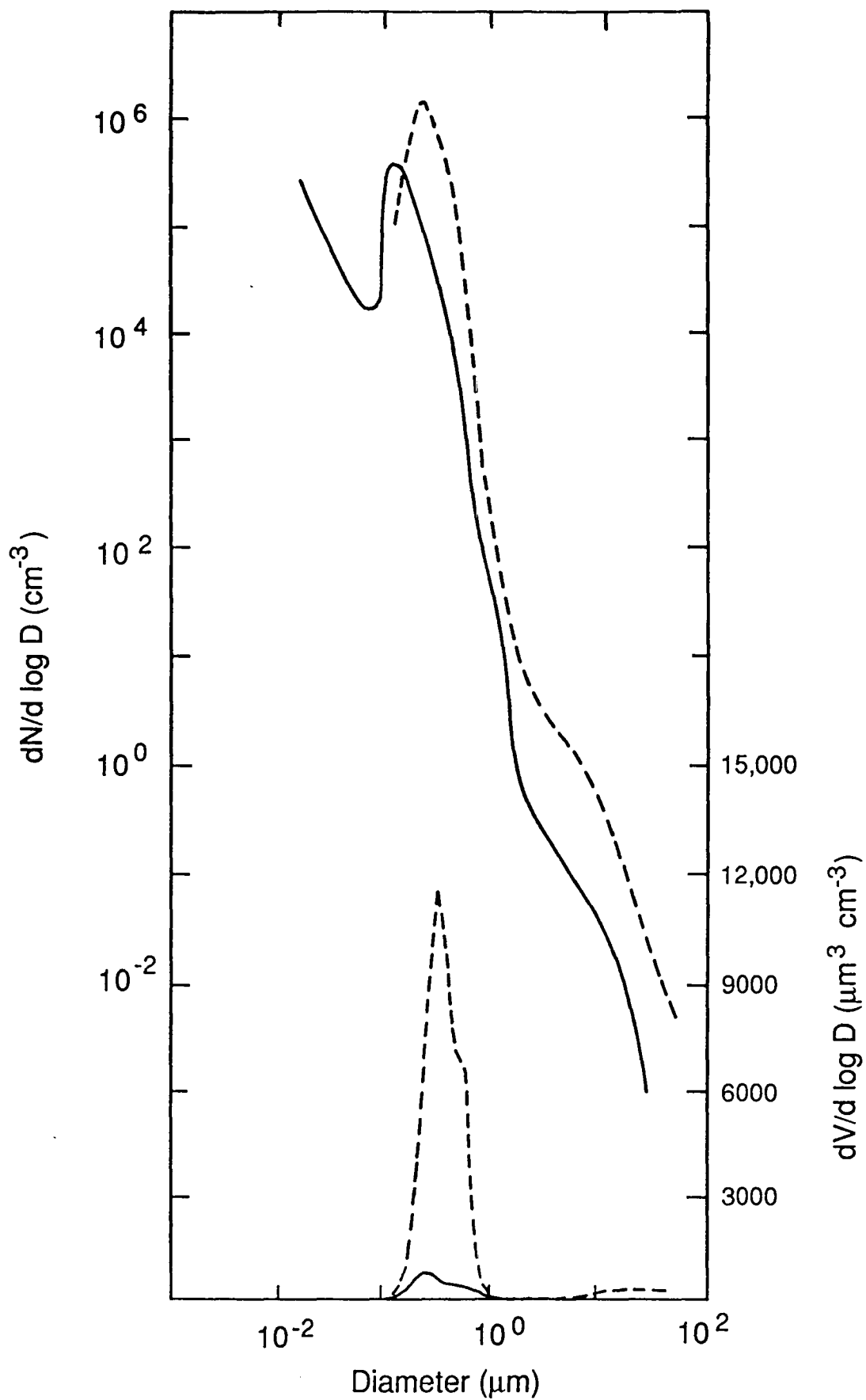


Figure VII C2.4 Mean particle number and volume spectra measured in two flaming phase column samples (A) and a smoldering phase column sample (B) at the Hill fire.

ignition, while the distributions with higher concentrations (curve B) were obtained from column samples taken below cloud base at least 70 minutes later. Therefore, in addition to the difference in number concentrations, we note that in both figures curve A represents smoke which is more characteristic of that produced during the early flaming combustion phase of the given fire, while curve B represents smoke which is more characteristic of that produced during the later smoldering phase of the given fire.

In these figures the nucleation mode is clearly evident for modest concentrations of particles, while at high concentrations a nucleation mode cannot be detected. In dense smokes such as these, coagulation is rapid and efficient, causing the peaks in the number and volume distributions to shift to larger diameters with increasing number concentration. This is observed in both Figures VII C2.3 and VII C2.4 and may help to explain the apparent disappearance of the nucleation mode at high concentrations of smoke.

Another process which may have influenced the particle size distributions at the Hill fire (Fig. VII C2.4) relates to the intensity of combustion. When compared to the smoldering phase number distribution (curve B), the flaming phase number distribution (curve A) shows a very pronounced fall-off in the heart of the accumulation mode resulting in a relatively very large shift in the modal (peak) diameter between the two curves. Unfortunately the possibility exists that much of this observed variation is an artifact resulting from the erratic behavior of the active scattering aerosol spectrometer (ASAS) during this flight (see section VII A2, p. 4). Nevertheless we take this opportunity to speculate.

The results of laboratory and in situ ground-based studies (Patterson and McMahon, 1984; Hardy and Ward, 1986; Ward, 1989) indicate that emissions of particulate matter (as measured by the computation of a particle emission factor) during smoldering combustion are relatively high and emissions of particulate matter during flaming combustion are relatively low (see section VII A.2). It is also well documented that darker smokes with higher contents of graphitic carbon are produced during flaming

combustion than during smoldering combustion when the smokes are relatively white (see section VII E). We therefore advance the hypothesis that charring and partial consumption of particles occurs to particles which are born by gas-to-particle conversion and coagulation within the flame envelope during flaming combustion. The charring effect would tend to darken the particles by increasing the elemental carbon fraction while the partial consumption effect would tend to reduce a given particle's diameter. If such a process were occurring, then Figure VII C2.5 would imply that the nucleation mode particles seen in curve A are largely born outside of the flame envelope.

Average number and volume distributions from ascending smoke column samples taken below cloud base (curve A) and smoke samples detrained from the capping cumulus cloud at the Wicksteed fires are shown in Figure VII C2.5. The data points shown in this figure correspond to the data summarized by curve B. We were unable to continue the line through them because an intermediate data point dropped off the bottom of the graph. The fact that the nucleation mode is diminished in the detrained smoke and the number and volume distribution peaks are shifted toward higher diameters relative to the column smoke suggests that the older detrained smoke has undergone more extensive coagulation than the younger column smoke. Also, there is the possibility that some of the particles, particularly those in the accumulation mode, were scavenged and released by the cloud. We would not expect nucleation mode particles to be efficiently scavenged because they are too small to serve as cloud condensation nuclei and their inertial masses are not of the magnitude required for efficient collision with cloud water droplets (see section VII F).

The Silver wildfire provided good data for examining the effects of smoke aging. Shown in Figure VII C2.6 are our measurements of particle number and volume distributions for smoke parcels of three ages within the plume.

Factors that could have played a role in changing the particle size distributions with downwind travel time (i.e. age) include dilution of the plume, the coagulation and sedimentation of particles, and variations in the fire itself. Dilution decreases the number

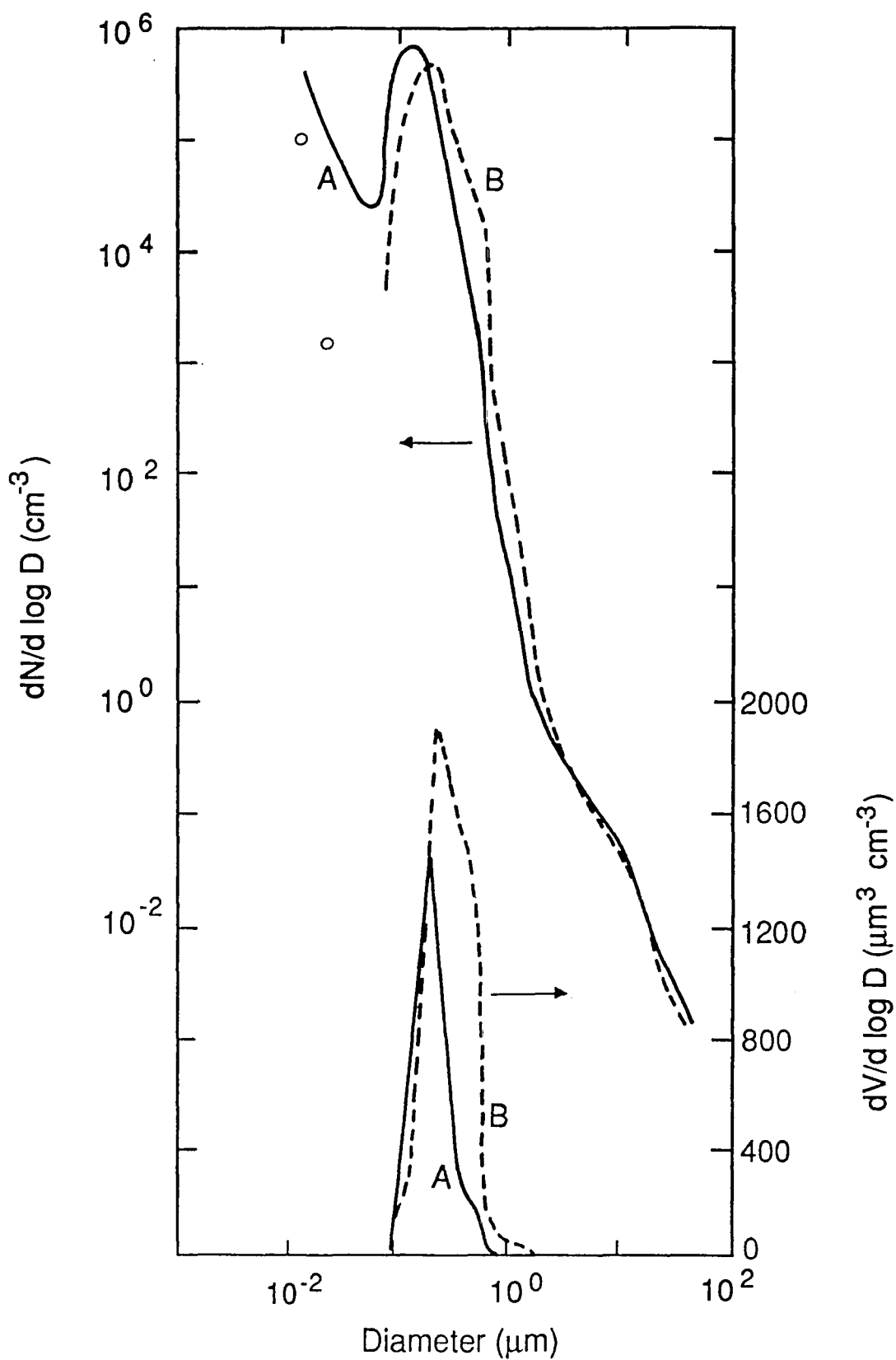


Figure VII C2.5 Mean particle number and volume spectra measured in four column samples (A) and two detained samples (B) at the Wicksteed fire.

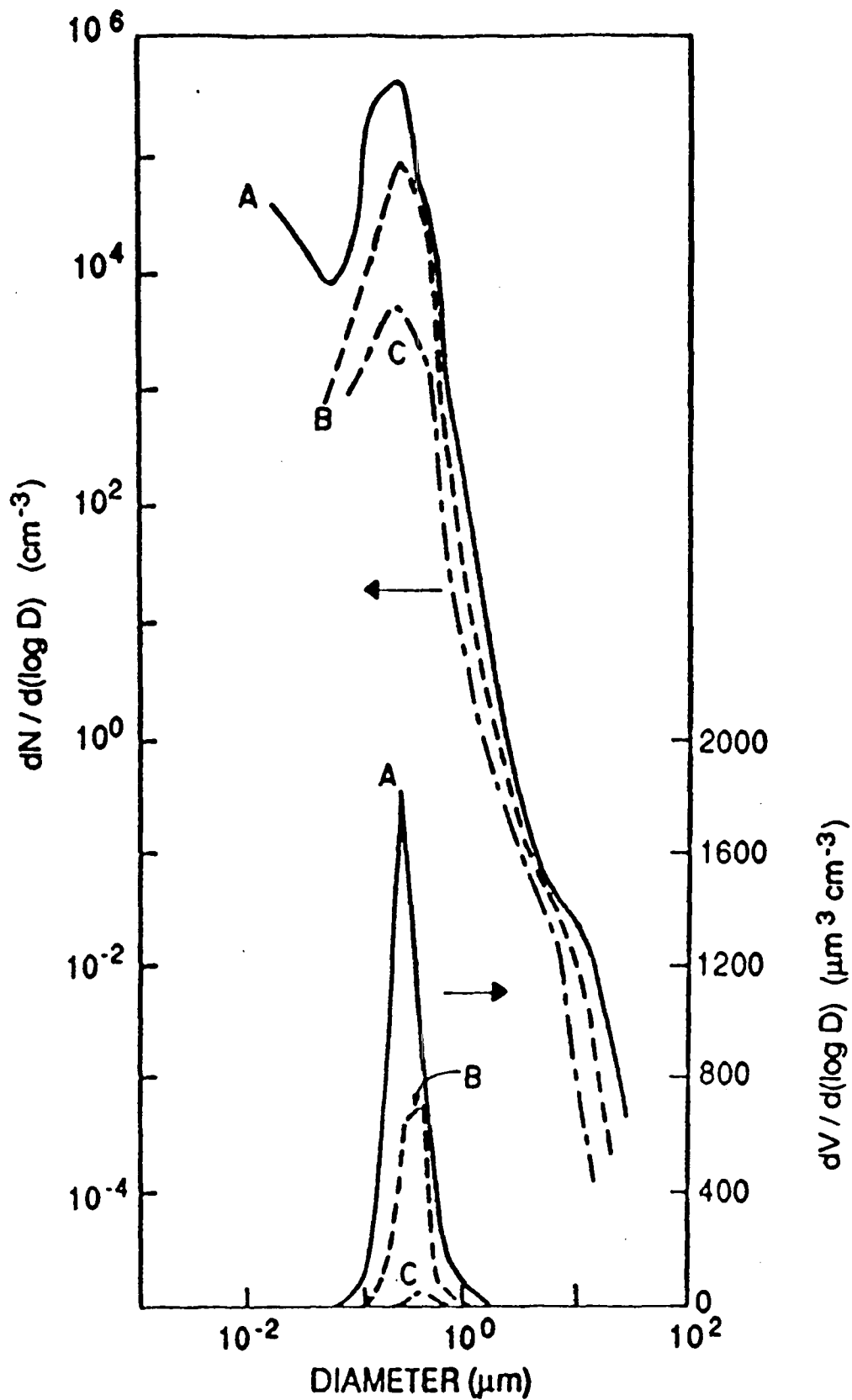


Figure VII C2.6 Particle number and volume spectra measured at the head of the Silver fire (A), at 10 hours (B), and 44 hours (C) travel time of the smoke downwind of the fire.

concentrations of particles in the plume; the effects of this can be seen in the number concentrations of particles with diameters $> 1.0 \mu\text{m}$.

The influence of coagulation is once again evidenced by the disappearance of the nucleation mode downwind over time. Also, in the accumulation mode of the particle volume spectra, the particle diameter (D_m) at which the volume concentration reaches a maximum value increases steadily with the age of the smoke up to 44 hours. The increase in the coagulation rate with increasing particle concentration (Fuchs, 1964) is borne out by the results shown in Figure VII C2.7. The geometric mean volume diameter of the particles in the accumulation mode generally increased with age for all samples. The rate of increase is positively correlated with the light-scattering coefficient due to dry particles (σ_{sp}), which is generally proportional to the mass concentration of particles in the accumulation mode (Waggoner et al., 1981).

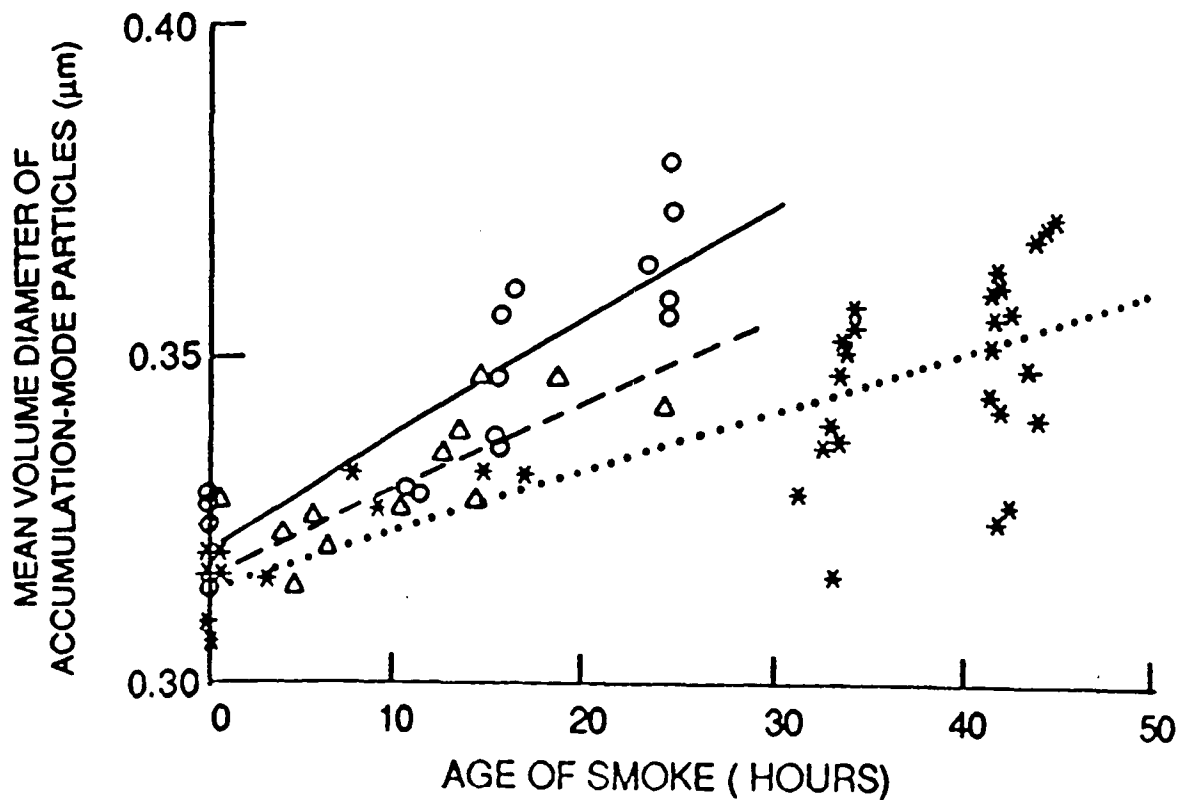


Figure VII C2.7 Geometric mean volume diameter of particles in the accumulation mode (0.2 – 2 μm diameter) as a function of the age of the smoke in the plume of the Silver fire. The measurements are grouped according to the value of the light-scattering coefficient due to dry particles as follows: Stars and dotted lines: $2 \times 10^{-4} \text{ m}^{-1} < \sigma_{\text{sp}} < 5 \times 10^{-4} \text{ m}^{-1}$ ($r = 0.89$); triangles and dashed lines: $5 \times 10^{-4} \text{ m}^{-1} < \sigma_{\text{sp}} < 10^{-3} \text{ m}^{-1}$ ($r = 0.77$); circles and solid lines: $\sigma_{\text{sp}} > 10^{-3} \text{ m}^{-1}$ ($r = 0.81$).

VII A.2. SMOKE EMISSIONS (ALOFT)

Carbon-Balance Method

Particle emission factors were determined using the carbon-balance method (Ward et al., 1982) adapted for airborne usage. The emission factor (EF) for particles in a specified size range is given by:

$$EF = \frac{\text{horizontal mass flux of particles}}{\text{fuel consumption rate}} \quad (1)$$

Therefore,

$$EF = \frac{\bar{P} A V}{F} \quad (2)$$

where $\bar{P}$ is the average mass concentration of the particles in a vertical cross-section of the plume, A is the cross-sectional area of the plume, V is the horizontal wind speed through the cross-section, and F is the fuel consumption rate. Since the carbon burned per unit time (C_B) is given by:

$$C_B = F C_f \quad (3)$$

where C_f is the fractional mass of carbon in the fuel, we have from Eqns. (2) and (3):

$$EF = \frac{\bar{P} A V C_f}{C_B} \quad (4)$$

If deposition of the particles is negligible and the plume is in steady state:

$$C_B = \left[(\overline{P}C_p) + (\overline{CO_2}C_{CO_2}) + (\overline{THC}C_{THC}) + (\overline{CO}C_{CO}) \right] AV \quad (5)$$

where, C_p , C_{CO_2} , C_{THC} , and C_{CO} are the fractional masses in the smoke plume of carbon in the particles, CO_2 , total hydrocarbons, and CO , respectively, and $\overline{CO_2}$, $\overline{THC}$, and $\overline{CO}$ are respectively, the average mass concentrations of CO_2 , total hydrocarbons, and CO in the plume cross-section. From Eqns. (4) and (5):

$$EF = \frac{\overline{P}C_f}{(\overline{P}C_p) + (\overline{CO_2}C_{CO_2}) + (\overline{THC}C_{THC}) + (\overline{CO}C_{CO})} \quad (6)$$

If it is assumed that the particles move with the gases, so that they bear the same ratio to each other from one point in the plume to another, an expression similar to Eqn. (6) will relate instantaneous measurements made at any point in the plume, where the average concentrations in Eqn. (6) would then be replaced by point concentrations. It is this latter modification of Eqn. (6) that we use to determine particle emission factors. Particle mass concentrations, over various size ranges, can be derived from the "grab" samples by measuring the particle size distribution, from weighing of filters through which the "grab" samples were passed, and from microbalance impactor measurements. The mass concentrations of the various carbon gases are obtained from GC-mass spectrometer analysis (Westberg et al., 1974; Rasmussen et al., 1974). C_p is measured through elemental carbon analysis of sequenced pyrolysis of quartz filters exposed to the smokes (Johnson et al., 1981). The value of C_f is taken as 0.5 (Bryam and Davis, 1959).

The derived emission factor is strictly valid only at the point of measurement. Any process that adds or removes a pollutant between the source and the location of the measurements will change the derived emission factor for that pollutant. Such changes are often small if the measurements are made close to the fire, while cloud scavenging and gas

and particle chemistry have the potential to significantly change the measured values of emission factors. The emission factors for particle mass given below were derived from measurements in smoke columns above the fire or at short distances downwind in stabilized smoke plumes. In some cases, however, the plume had been scavenged by capping cumulus clouds.

Particle Emission Factors

Shown in Figure VII A2.1 are the particle emission factors as a function of time for the Lodi 1 fire. Excellent agreement was achieved between the three independent measurements of particle mass concentrations shown in this figure. This was usually the largest source of experimental error involved in the computation of particle emission factors. Mass concentrations derived from the size distribution of particles were estimated by multiplying an appropriately integrated particle volume by a calculated or assumed mean particle density for a given sample. Particle densities were computed by comparing microbalance impactor measurements of particle mass concentration (the mean mass cutpoint diameter for this instrument is $2.0\text{ }\mu\text{m}$) with a simultaneously measured particle volume integrated up to $2.0\text{ }\mu\text{m}$. For any given fire the mean particle density normally fell between 1.0 and 2.0 g/cm^3 . During the Hill fire, however, there was an unexpected degree of variation among the computed densities with a mean value of about 3.5 g/cm^3 . Estimated densities for the Wicksteed fire, flown two days subsequent to Hill, showed much less variation, however the mean value dropped to less than 0.5 g/cm^3 . Particle densities estimated in a less precise manner by comparing integrated particle volumes with mass concentrations measured from weighed filters through which coincident samples of air were passed produced similar results (before the air passed through the filters it was centrifuged to remove large particles; the mean mass cutpoint diameter here was $3.5\text{ }\mu\text{m}$). This was an ominous development portending a possible problem with a portion of our particle measuring system. At times in the past we have discovered that the laser can be

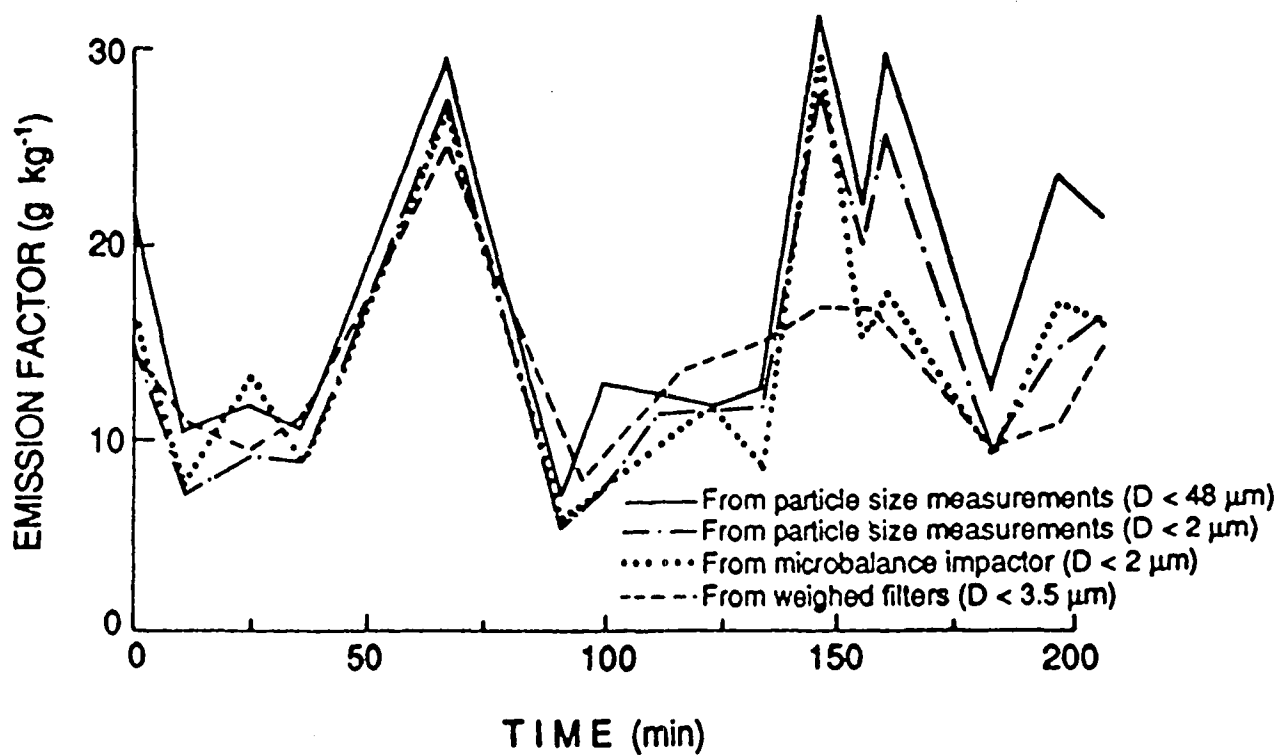


Figure VII A2.1 Emission factors for particle mass as a function of time after ignition for the Lodi 1 fire.

jolted out of proper alignment in the ASAS particle size measuring instrument.

Considering the violence of our encounters with the Hill and Wicksteed fires this now seems likely. This misalignment causes negligible error in particle size, but can introduce a significant error in concentration. We are currently investigating correction techniques using the relationship between accumulation mode mass and the light scattering coefficient. The two 1989 flights prior to Hill (Summit and Carbonado) and the sole flight subsequent to Wicksteed (Mabel Lake) also showed mean particle densities below 0.5 g/cm^3 . As a result, there is a fair amount of speculation inherent in our computation of emission factors derived from the volume distribution of particles for these five fires. For the Hill fire we assumed a value of 3.0 g/cm^3 for the particle density. For Wicksteed, Summit, Carbonado, and Mabel Lake 1.0 g/cm^3 was the assumed value. These choices are loosely based on our own previous work in addition to the results of Stith *et al.* (1981) who computed average particle densities close to 1.0 g/cm^3 for three fires in the Pacific Northwest, and Einfeld *et al.* (1989) who computed an average value of 1.8 g/cm^3 for three fires in Southern California.

These developments emphasize the importance of multiple techniques and especially for the Hill and Wicksteed fires the weighed filter samples must be considered to yield the most reliable data.

Laboratory and in situ ground based studies (Patterson and McMahon, 1984; Hardy and Ward, 1986; Ward, 1989) have shown that particle emissions are strongly dependent upon the intensity of combustion. In general, the early flaming phase of combustion is most efficient and produces relatively low emissions of particulate matter, while the later smoldering phase of combustion is less efficient and produces relatively high emissions of particulate matter. Airborne observations, on the other hand, provide only weak support at best for this phenomenon and at times may be altogether contradictory. The temporal behavior of the particle emission factors from Lodi 1 is in stark contrast to that of ground based studies in that the peaks seen in Figure VII A2.1 appear to correspond to periods

when the fire was intense and spreading rapidly. The airborne study of Stith et al. (1981) reports similar behavior. Such discrepancies suggest that there could be chemical processes occurring well above ground-based instrument platforms which are capable of adding very significant quantities of particle mass to the plume at higher altitudes during flaming combustion. Recently, however, it has been suggested by Cofer et al. (1989) and Ward (1989) that there is an optimum level of intensity for most efficient burning in open fires which depend on turbulent airflows to supply them with oxygen for combustion. Cofer et al. (1989) contend that in raging fires characterized by very intense flaming phase combustion there may be oxygen depletion or thermal quenching of oxidation reactions prior to completion. The result would be a higher production of particulates. Many of the fires studied showed pronounced increases in particle emission factors as the fire became increasingly oxygen-limited. One example is the Battersby fire shown in Figure VII A2.2. Here we use the ratio of CO to CO₂ as the indicator of oxygen availability in the plume with high ratios suggesting limited oxygen (see section VII C3). Particulate masses used in these calculations were determined by weighing teflon filters through which samples from the plume were drawn. Since the very active periods of flaming are most easily noticed from an aircraft this could help to explain the observations at Lodi 1 and those of Stith et al. (1981).

In any event, the above discussion is somewhat precluded by the difficulties involved in distinguishing between smoke from flaming combustion and smoke from smoldering combustion at higher altitudes from an airborne platform. Ward (1989) and Cofer et al. (1989) have underscored this problem. Combustion conditions in the fuel bed are seldom homogeneous and smoldering phase emissions can easily overwhelm flaming phase emissions for many fuel types. Such difficulties are most pertinent during the larger prescribed burns when it becomes difficult to ignite the entire burn area instantaneously. Often the period of ignition for a large prescribed burn may last over an hour, or there may be subsequent attempts to re-ignite fuel that was not completely consumed after the original

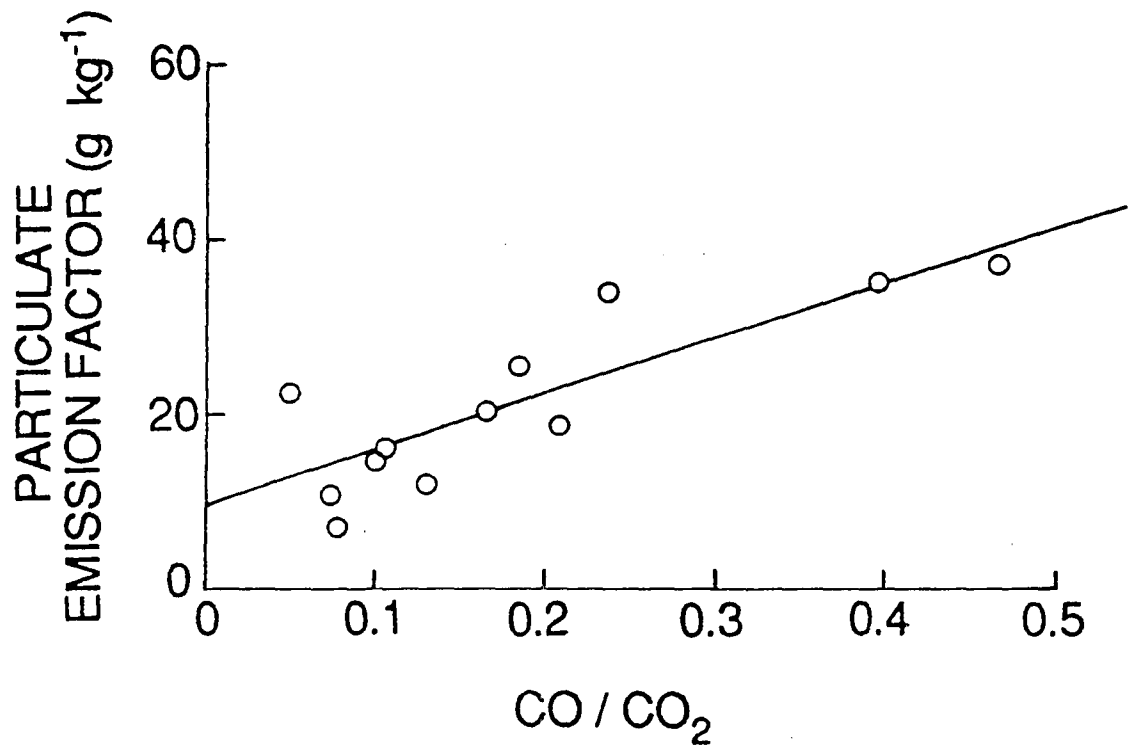


Figure VII A2.2 Emission factor for particulates as a function of the CO/CO₂ concentration ratio in the plume from the Battersby fire.

ignition. Consequently the best we can do is to make broad qualitative judgements as to which phase of combustion best characterizes the conditions at the origin of a given smoke sample. Usually we base this judgement simply on the age of the fire.

Airborne measurements in the ascending column and downwind plume do, however, have some distinct advantages over ground based samples. Rapid turbulent mixing quickly produces a fire integral emission in most cases prior to the collection of airborne samples. Thus each one of our samples characterizes essentially the entire fire at some broad point in time while point samples on the ground are generally far too sparse to sensibly integrate over area, especially for large fires.

One fire which showed a fairly steady increasing trend in the particle emission factor with time was the Mabel Lake fire shown in Figure VII A2.3. This fire was of modest size (29 ha) and was very rapidly ignited so that flaming phase combustion dominated the early portion of the fire. Subsequently there was a smooth transition through a mixed phase and into the smoldering phase of combustion. In Figure VII A2.3 we show emission factors which were computed from weighed filters through which samples of smoky air were passed which had not been centrifuged to remove large particles. These samples produced emission factors which were generally larger than those computed from filtered samples of air which had been centrifuged producing a mean cutpoint diameter of $3.5\text{ }\mu\text{m}$. Our emission factors derived from the volume distribution of particles with diameters $<2\text{ }\mu\text{m}$ were larger still, however, suggesting that our chosen value for the mean particle density (1.0 g/cm^3) was too high. Nevertheless, the average of these four curves shows that emission factors increased steadily from a low of 6.4 at 18 minutes after ignition to a high of 18.4 at 81 minutes after ignition. All of these samples were taken in the ascending smoke column. The Troy fire (70 ha) also showed a marked increasing trend in the particle emission factor with time. While similar, this trend was less steady than that depicted for Mabel Lake.

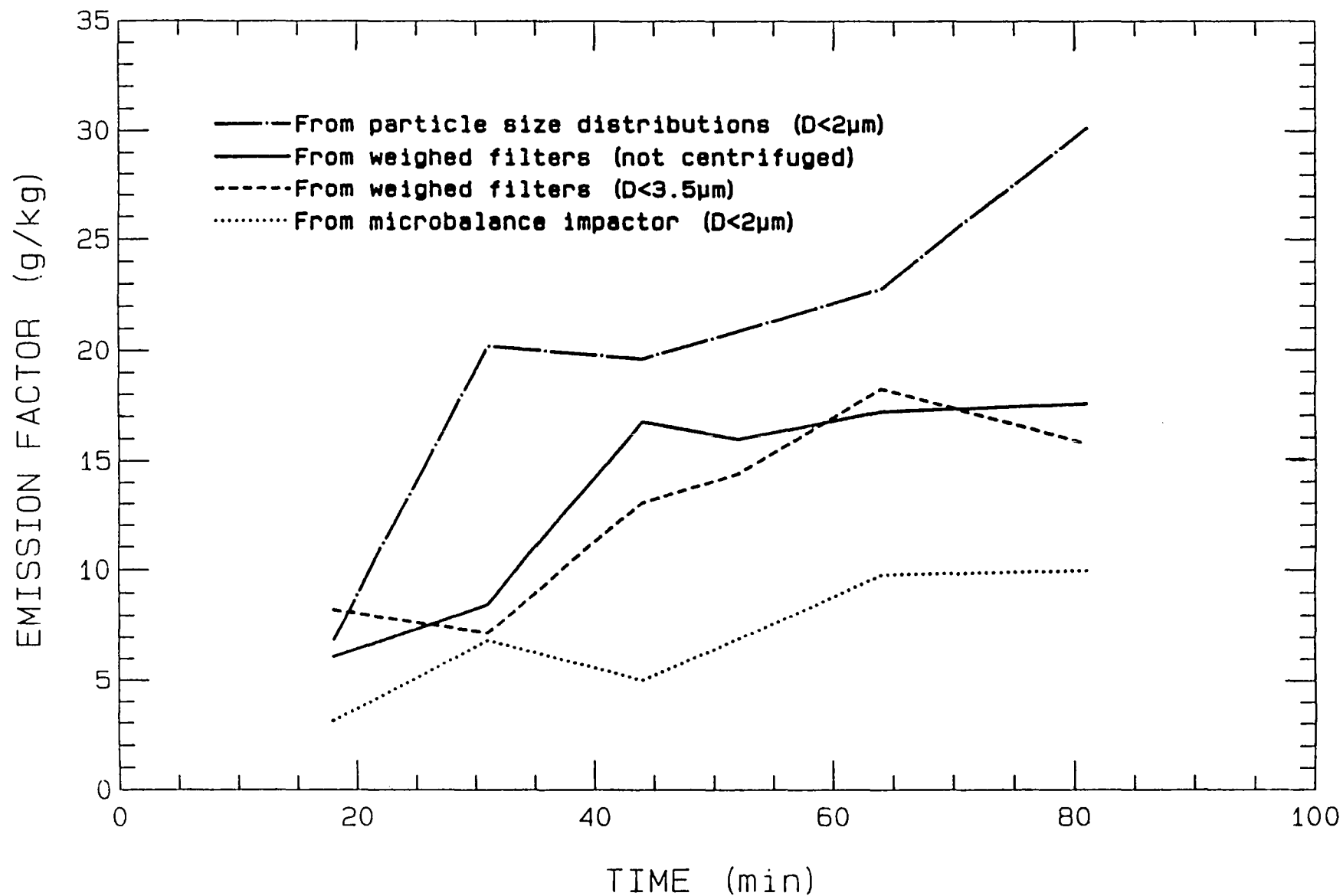


Figure VII A2.3 Emission factors for particle mass as a function of time after ignition for the Mabel Lake fire.

Emission factors for the Abee fire (Fig. VII A2.4) increased rapidly over the first 25 minutes of combustion. During the initial 10 to 15 minutes the smoke column was capped by a vigorous cumulus cloud which may have significantly scavenged the downwind plume where all of our measurements were made. The extent to which the relatively low emission factors during this period were caused by more efficient flaming combustion immediately following ignition is therefore unclear.

Average particle emission factors from the seventeen biomass fires are listed in Table VII A2.I. The high standard deviations reflect the sensitivity of the unaveraged emission factors to temporal influences such as the intensity of combustion. While there is clearly merit in partitioning the data from each of the fires, we chose to emphasize the average emission factors. For a given fire, this average value is our best characterization of the amount of smoke lofted at least to mid-tropospheric levels.

The weighed filter method of measuring particle mass concentrations produced an overall average emission factor of 15.0 g/kg for particles with diameters $<3.5\ \mu\text{m}$ (hereafter these will be referred to as $\text{PM}_{3.5}$ emission factors). This estimate has a standard deviation of 10.6 g/kg and comes from a sample of 81 measurements from 14 of the 17 fires. The overall average emission factor derived from the volume distribution of particles with diameters $<2.0\ \mu\text{m}$ (hereafter called $\text{PM}_{2.0}$) was slightly greater at 16.4 g/kg with a standard deviation of 13.2 g/kg. This sample consisted of 112 measurements from all 17 fires. The fact that the former overall mean estimate is less than the latter is not entirely unexpected. One will notice that for a given fire there can be significant differences between the two methods of computing emission factors. Part of this, no doubt, is a systematic result stemming from our choice for the mean particle density for that fire. We should also point out, however, that the particle measuring instruments feed off of a separate grab sample bag from the one which feeds into the filter housing and the instruments which measure trace gas concentrations. On occasion the two bags sampled independently, and the two methods produced independent results. Even when the bags

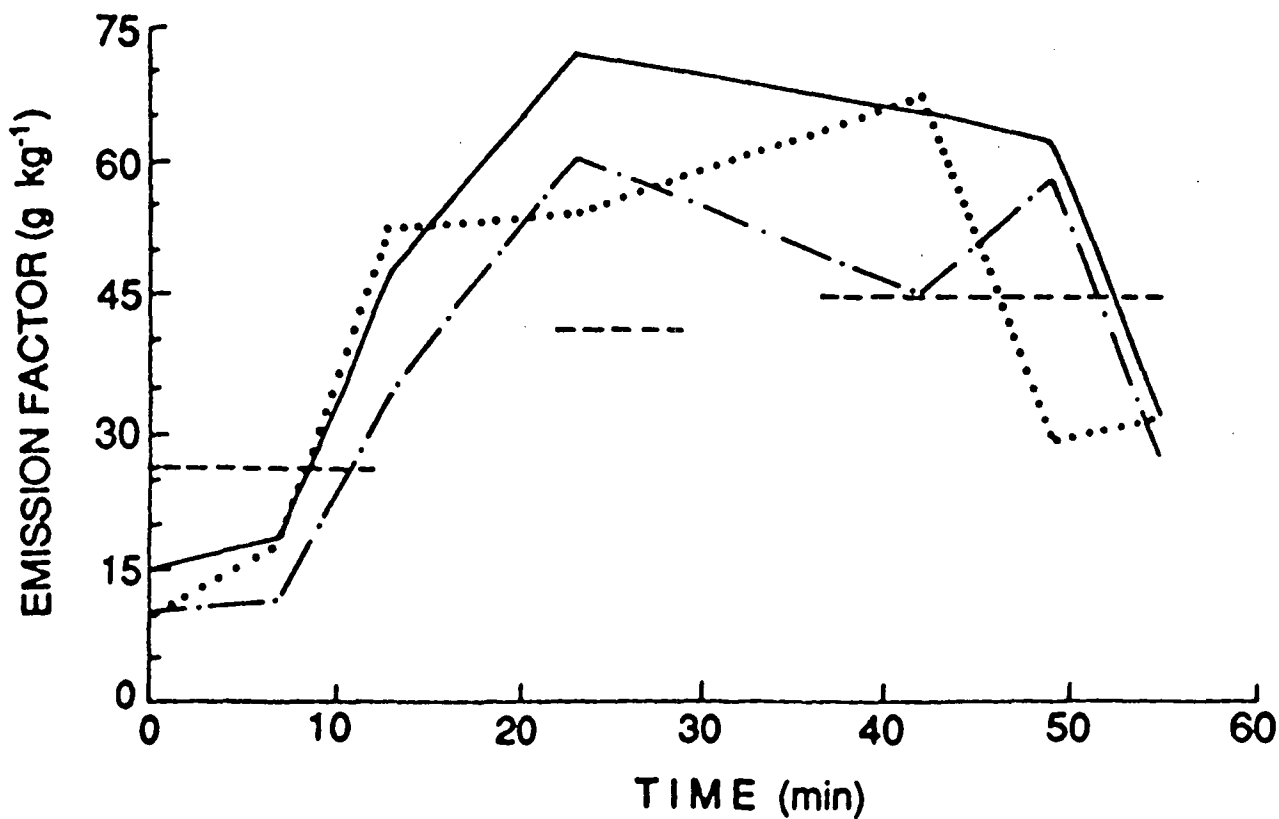


Figure VII A2.4 Particle emission factors as a function of time after ignition from the beginning of observations on the Abee fire. A vigorous cumulus cloud capped the smoke column for the first 10 – 15 min. The measurements were made downwind of this capping cumulus in the stabilized plume. (Data key as in Fig. VII A2.1).

Table VII. A2.I PARTICLE EMISSION FACTORS (IN GRAMS OF SMOKE PER KILOGRAM OF FUEL BURNED) AND SINGLE-SCATTERING ALBEDO AND SPECIFIC ABSORPTION FOR ALL FIRES STUDIED

Emission factor (derived from size distribution of particles < 2 μm diameter)			Emission factor (from weighed filters containing particles < 3.5 μm diameter)			Emission factor (derived from size distribution of particles < 48 μm diameter)			Mean value of single-scattering albedo $\tilde{\omega}$ ($= \sigma_s / \sigma_E$)	Mean values of specific absorption B_A ($\text{m}^2 \text{g}^{-1}$)	
Mean	Standard Deviation	Number of Samples (N)	Mean	Standard Deviation	Number of Samples (N)	Mean	Standard Deviation	Number of Samples (N)			
BIOMASS FUELS											
Abee	35.1	20.3	7	37.4	9.8	3	44.5	23.1	7	ND	ND
Eagle	7.9	5.7	8	11.3	4.8	2	10.8	6.0	8	0.85 (N = 2)	0.67 (N = 2)
Lodi 1	14.3	7.3	16	13.5	4.4	13	17.6	7.9	16	0.89 (N = 13)	0.74 (N = 13)
Lodi 2	15.5	6.5	9	23.0	19.6	8	17.7	7.0	9	0.80 (N = 7)	0.68 (N = 1)
Hardiman	16.2	12.4	11	10.5	3.0	9	21.7	14.6	11	0.87 (N = 9)	0.79 (N = 5)
Wheat	43.8	---	1	ND	---	---	47.9	---	1	NA	ND
Myrtle/FallCreek*	19.5	12.1	10	6.1	3.1	8	29.3	16.5	10	0.84 (N = 4)	0.73 (N = 16)
Silver*	26.4	13.6	2	20.2	12.7	3	32.5	17.1	2	0.90 (N = 2)	0.36 (N = 2)
Satsop	24.6	7.1	2	12.0	---	1	34.3	10.8	2	0.86 (N = 1)	0.38 (N = 1)
Troy	17.1	12.4	5	9.7	3.0	5	30.2	19.5	5	0.82 (N = 3)	0.82 (N = 3)
Battersby	18.2	21.1	11	20.9	10.6	11	20.3	20.7	11	0.84 $\pm$ 0.05 (N = 7)	0.89 (N = 4)
Peter Long	ND	ND	ND	16.9	5.1	4	ND	ND	ND	0.84 $\pm$ 0.05 (N = 4)	1.39 (N = 2)
Hill	5.5	3.5	6	10.2	6.5	3	6.9	4.3	6	0.84 $\pm$ 0.04 (N = 3)	0.59 $\pm$ 0.22 (N = 4)
Hornepayne	12.9	9.1	10	10.8	4.7	5	13.3	9.1	10	0.60 $\pm$ 0.21 (N = 6)	0.66 $\pm$ 0.52 (N = 5)
Carbonado	10.7	7.6	7	ND	---	---	11.1	7.9	7	0.89 (N = 9)	ND
Summit*	17.6	4.1	2	ND	---	---	18.33	4.4	2	0.82 (N = 5)	ND
Mabel Lake	19.9	8.4	5	12.8	4.3	6	23.4	5.9	3	0.82 (N = 12)	0.41 $\pm$ 0.06 (N = 14)
Averages	16.4	13.2	112	15.0	10.6	81	21.2	15.4	110	0.83 $\pm$ 0.11 (N = 83)	0.64 $\pm$ 0.36 (N = 73)
FOSSIL FUELS											
Tyndall (JP4)	0	0	0	23.1	15.0	21	0	0	0	0.32 (N = 11)	4.10 (N = 10)

* Wild fires
 0 Particle data suspect due
 to particle composition
 NA - Not analyzed
 ND - No data

were sampling coincidentally there always were slight differences in the filling times for each bag. Since the filter housing and the trace gas instruments are both fed by the same grab sample bag, and because of the earlier revelations concerning estimates of particle mass concentrations derived from particle volume distributions, we feel that the weighed filter method of computing particle emission factors is the most consistent and reliable.

The overall average emission factor derived from the volume distribution of particles with diameters $<48\text{ }\mu\text{m}$ (PM₄₈) was calculated to be 21.2 g/kg with a standard deviation of 15.4. The PM₄₈ emission factors were computed in a manner identical to that used to compute PM_{2.0} emission factors with the exception that mass concentrations were inferred from particle volumes integrated over the entire size range of our measurements. When the overall PM_{2.0} emission factor is compared to the overall PM₄₈ emission factor it becomes evident that the majority of emitted PM₄₈, about 80%, is contained in particles with diameters $<2.0\text{ }\mu\text{m}$.

Except for the Wheat fire, for which we have only one observation, the Abec fire produced the highest emission factors in these studies. The PM_{3.5} data indicate that the Hardiman, Myrtle/Fall Creek, Satsop, Troy, Hill, and Wicksteed fires all had relatively low emissions. Each of these fires also produced a capping cumulus cloud at some time during the period of measurements.

Our observations of several fossil fuel fires (only one fuel type, aviation JP-4 fuel) produced an average PM_{3.5} emission factor of 23.1 g/kg. This was considerably higher than the overall average PM_{3.5} emission factor for the biomass fires. The particles themselves were relatively strong light absorbers, and a large fraction of them were agglomerated producing severe departures from sphericity. The particle volume distributions were highly suspect, consequently, and the PM_{2.0} and PM₄₈ emission factors were not computed.

The PM_{3.5} emission factors for Hill and Wicksteed were 10.2 ± 6.5 and 10.8 ± 4.7 respectively. The first Hill sample produced a very low emission factor of 2.8 g/kg at 32

minutes after ignition. This sample was taken in the capping cumulus cloud. The other two samples were taken in the column below cloud base and produced emission factors of 15.0 g/kg and 12.7 g/kg at 78 and 105 minutes after ignition, respectively.

The PM_{3.5} emission factors at Wicksteed also started very low at 3.7 g/kg. This came from a column sample taken below cloud base only 6 minutes after ignition. The next sample, taken at 38 minutes after ignition from smoke which had detrained from the cumulus cloud, produced an emission factor of 12.1 g/kg. The remaining three samples were taken in the downwind trailing portion of the cloud and ranged from 16.8 to 10.5 g/kg generally decreasing with time.

The average PM_{3.5} emissions factors for Hill and Wicksteed compare most favorably with the Hardiman fire also flown near Chapleau, Ontario in August of 1987. These three fires produced mean PM_{3.5} emission factors which were below the average for all 17 fires. The other two large Canadian fires (Battersby and Peter Long) were flown near Timmins, Ontario and produced mean PM_{3.5} emission factors which exceeded the overall average.

VII.C.3. TRACE GAS EMISSIONS

Introduction

Emissions of trace gases from biomass burning are known to be an important source of several trace gases (such as CO₂, CO, and CH₄) in the atmosphere (Crutzen *et al.*, 1985). In addition, local and regional air quality can be greatly affected by the emissions from fires (Radke *et al.*, 1978). Nevertheless, quantitative assessments of the contributions of these emissions to the global budgets of certain trace gases are difficult to make. The main difficulty in formulating such estimates arises from the fact that biomass burning worldwide is not well quantified: either as to area or biomass amount. There are, of course, also limitations in the data set for diverse fuel beds and we know of some remarkable variances in similar fuels in different locations. Despite these shortcomings the emissions from various biomass fires have considerable consistency.

Nevertheless, the quantity and breadth of the trace gas data gathered in this series of measurements not only warrants attention in its own right, but encourages its use for extrapolation to global scales. Global scale extrapolation is interesting for its "global change" implications, but is more important for providing what is essentially a normalization technique with which one can standardize one's values for comparison with both other studies of similar processes or of competing processes. It thus affords one the ability to do budget calculations. The contributions of emissions from fires to global trace gas fluxes can be calculated using available estimates of the amounts of CO and CO₂ produced annually from biomass burning (e.g. Crutzen *et al.*, 1985; Mooney *et al.*, 1987). To make use of this information, the relative emission ratio of each trace gas to CO (or CO₂) was calculated using the data in Table VII C3.I. This value was then multiplied by the estimated worldwide emission flux of CO (or CO₂) from biomass burning, producing an estimate of the contribution of emissions from fires to the global flux of the trace gas. Our estimates for CO₂ emissions (see Table VII C3.I) are, in general, higher than

VII.C.3.1

Table VII C3.I. Average emission factors (and standard deviations) for various trace gases from ten biomass fires in North America. With the exception of O₃ and NH₃, for which values are based on continuous measurements and filters, respectively, all values shown are based on the analyses of samples collected in steel canisters. Units are g kg⁻¹. [Adapted from Hegg *et al.* (in press)].

Fire	CO	CO ₂	O ₃	NH ₃	CH ₄	C ₃ H ₆	C ₂ H ₆	C ₃ H ₈	C ₂ H ₂	N-C ₄ *	N ₂ O	F12**	NO _x ***
Lodi 1	74 ± 16	1664 ± 44	14 ± 13	1.7 ± 0.8	2.4 ± 0.15	0.58 ± 0.05	0.35 ± 0.12	0.21 ± 0.12	0.32 ± 0.05	0.11 ± 0.07	0.31 ± 0.14	0.045 ± 0.010	8.9 ± 3.5
Lodi 2	75 ± 14	1650 ± 31	0.19 ± 0.36	0.09 ± 0.04	3.6 ± 0.25	0.46 ± 0.03	0.55 ± 0.15	0.32 ± 0.12	0.21 ± 0.03	0.10 ± 0.05	0.27 ± 0.31	0.009 ± 0.003	3.3 ± 0.8
Myrtle/ Fall Creek	106 ± 20	1626 ± 39	-0.5 ± 0.2	2.0 ± 0.9	3.0 ± 0.8	0.7 ± 0.04	0.60 ± 0.13	0.25 ± 0.05	0.22 ± 0.04	0.02 ± 0.04	—	0.0025 ± 0.0015	2.54 ± 0.70
Silver	89 ± 50	1637 ± 103	4.7 ± 4.0	0.6 ± 0.5	2.6 ± 1.6	0.08 ± 0.01	0.56 ± 0.33	0.42 ± 0.13	0.19 ± 0.09	0.2 ± 0.1	0.27 ± 0.39	0.0	0.81 ± 0.65
Hardiman	82 ± 36	1664 ± 62	-0.5 ± 0.4	0.1 ± 0.07	1.9 ± 0.5	0.58 ± 0.09	0.45 ± 0.26	0.18 ± 0.13	0.31 ± 0.35	0.02 ± 0.04	0.41 ± 0.52	0.0004 ± 0.0003	3.3 ± 2.3
Eagle	34 ± 6	1748 ± 11	6.5 ± 2.9	---	0.9 ± 0.2	0.25 ± 0.06	0.18 ± 0.05	0.05 ± 0.02	0.08 ± 0.02	0.2 ± 0.08	0.16 ± 0.013	0.008 ± 0.003	7.2 ± 3.8
Battersby	175 ± 91	1508 ± 161	-0.9 ± 0.6	---	5.6 ± 1.7	0.9 ± 0.15	0.57 ± 0.45	0.27 ± 0.12	0.33 ± 0.06	0.07 ± 0.06	---	---	1.05 ± 1.33
Hill	90 ± 21	1646 ± 50	-0.29 ± 0.12	---	4.2 ± 1.3	0.65 ± 0.19	0.48 ± 0.17	0.15 ± 0.06	0.25 ± 0.05	0.04 ± 0.01	0.18 ± 0.06	0.0	---
Home- Payne	55 ± 41	1700 ± 82	-1.25 ± 1.16	---	3.8 ± 2.8	0.62 ± 0.40	0.51 ± 0.34	0.17 ± 0.12	0.22 ± 0.12	0.04 ± 0.03	0.22 ± 0.14	0.0017 ± 0.0022	---
Mabel Lake	83 ± 37	1660 ± 70	-0.3 ± 0.4	---	3.5 ± 1.9	0.46 ± 0.21	0.38 ± 0.21	0.11 ± 0.07	0.22 ± 0.06	0.03 ± 0.01	0.04 ± 0.05	0.0	---
OVERALL AVERAGE EMISSION FACTOR	83 ± 16	1650 ± 29	2.2 ± 1.6	0.90 ± 0.43	3.2 ± 0.5	0.53 ± 0.08	0.46 ± 0.08	0.21 ± 0.05	0.24 ± 0.04	0.083 ± 0.028	0.23 ± 0.05	0.0074 ± 0.0051	3.9 ± 16

* Straight chain paraffin with carbon number of 4.

** CF₂Cl₂

*** NO_x = NO + NO₂

published values. Consequently, CO has been used as the "ratio species" in our estimations of global fluxes.

Table VII C3.II lists the mean emission factor ratios for certain trace gas species, as well as the estimated fluxes from global biomass burning found using these ratios. The value for worldwide CO emissions due to biomass burning used in calculating the fluxes was 800 Tg yr^{-1} (Crutzen *et al.*, 1985). By way of comparison, a calculation using Radke's (1989) estimate of $\sim 10^4 \text{ Tg yr}^{-1}$ of biomass burned globally and our emission factor for CO yields an essentially identical global flux of 910 Tg yr^{-1} of CO.

Results

O₃, the first species listed in Table VII C3.II, is not emitted directly during combustion of biomass but is instead the product of the chemical interaction of reactive hydrocarbons and NO_x in the smoke plume (Evans *et al.*, 1974; Radke *et al.*, 1978). The correlation between available NO_x and the production of O₃ can be examined by studying the relationship between our emission factors for O₃ and NO_x. A linear regression of the O₃ emission factor onto the NO_x emission factor (based on the data in Table VII C3.1) results in an intercept of -2.2 Tg yr^{-1} , a slope of 1.4, and a correlation coefficient (*r*) of 0.8 significant at the 98% confidence level. This analysis suggests that O₃ is produced in smoke plumes in a process similar to that involved in photochemical smog production. As has been discussed previously (see Dimitriodes and Dodge, 1983), the mechanism responsible for O₃ production is apparently regulated by the availability of NO_x. If the amount of NO_x in the plume is insufficient to react with the available reactive hydrocarbons, O₃ will not be produced. Correspondingly, the production of O₃ increases with increasing NO_x.

The contribution of emissions from biomass burning to global ozone fluxes can also be assessed using our results. Total tropospheric O₃ production has been estimated to be on the order of $\sim 4,000 \text{ Tg yr}^{-1}$ (Hegg *et al.*, in press). This is two orders of magnitude

Table VII C3.II. Mean values of EF_x/EF_{CO} for biomass burning (where EF_x is the emission factor of trace gas species x and EF_{CO} the emission factor of CO) calculated from the data listed in Table VII C3.1*. Also shown are estimates of the global fluxes of various trace gases from biomass burning based on the EF_x/EF_{CO} ratios and estimates of worldwide CO emissions from biomass burning from Crutzen *et al.* [1985]. [Adapted from Hegg *et al.* (in press)].

Species	EF_x/EF_{CO}			Estimated Flux from Biomass Burning Worldwide ($Tg\ yr^{-1}$)	Estimated Contribution of Biomass Burning to Worldwide Flux of Species (%)
O ₃	0.04	±	0.03	32	1
NH ₃	0.01	±	0.008	8	50
CH ₄	0.04	±	0.008	32	~7
C ₃ H ₆	0.007	±	0.001	6	?
C ₂ H ₆	0.006	±	0.001	5	?
C ₃ H ₈	0.003	±	0.0007	2.4	?
C ₂ H ₂	0.003	±	0.0006	2.4	?
N-C ₄	0.001	±	0.0007	0.8	?
N ₂ O	0.003	±	0.001	2.4	16
F ₁₂	0.0001	±	0.00007	0.08	20
	(0.00005	±	0.00003)**	(0.04)**	(10)**
NO _x	0.07	±	0.04	56	40

* The mean values of EF_x/EF_{CO} were obtained by first ratioing the values of EF_x to EF_{CO} for each of the fires listed in Table VII C3.1 and then averaging these ten ratios.

** A more conservative estimate obtained by eliminating results from the Lodi I fire.

greater than the value for the global flux of O_3 listed in Table VII C3.II (32 Tg yr^{-1}). Consequently, O_3 resulting from biomass burning is a modest source of tropospheric ozone.

Based on our data, the estimated flux of NH_3 from global biomass burning is on the order of $\sim 8 \text{ Tg yr}^{-1}$. This value represents roughly 50% of the total worldwide flux of the species, thereby substantiating a previous assertion (see Hegg et al., 1988) that emissions from biomass burning are a significant source of atmospheric NH_3 . This very important result has directly resulted from this program.

Data on NH_3 emissions is not available for the Battersby, Hill and Wicksteed biomass fires. We are, however, in the process of analyzing NH_3 data for the Mabel Lake prescribed burn. Study of these results will hopefully enable us to further quantify the hypothesis that biomass burning is a significant source of atmospheric NH_3 .

A study of biomass fires in the Amazon Basin by Andreae et al. (1988) yielded measurements of significant fluxes of particulate NH_4^+ . The authors postulated that if these emissions also contained large amounts of gaseous NH_3 (which they did not measure), the contribution of biomass burning to the global flux of NH_3 would be quite substantial. As is outlined by Hegg et al. (in press), our global flux estimate for NH_3 corresponds to $\sim 7 \text{ Tg yr}^{-1}$ of NH_3 and is approximately twice the flux of NH_4^+ from biomass fires (as estimated by Andreae et al.). If the fluxes of NH_4^+ and NH_3 are assumed to be additive, one obtains a combined flux of $\sim 10 \text{ Tg yr}^{-1}$. This flux would be the most significant contributor to the atmospheric NH_3 reservoir (see Galbally, 1985).

The estimated worldwide flux of CH_4 listed in Table VII C3.2II (32 Tg yr^{-1}) agrees favorably with previously calculated values (for example, Crutzen et al. (1985)) obtained a global flux of $40 \text{ Tg } CH_4 \text{ yr}^{-1}$). Furthermore, the measurements of CH_4 emissions from the ten fires illustrate an important characteristic of biomass fires. As is discussed by Hegg et al. (in press), the ratio of CO to CO_2 in a smoke plume serves as an indicator of the extent of oxidation in a plume with high ratios suggesting that only limited oxygen is

available. In such an oxygen-limited environment, the amount of CH_4 produced would be expected to be higher due to greatly increased H_2 levels. This correlation between CO to CO_2 ratios and increased CH_4 emissions is illustrated by a linear regression of the CH_4 emission factor onto the ratio of CO to CO_2 emission factors using the data in Table VII C3.1. Such a calculation yields a correlation coefficient (r) of 0.75 significant at > 98% confidence level, thus suggesting that biomass fires are often oxygen limited. A graphical presentation of this regression analysis is given in Figure VII C3.1.

An analysis focusing exclusively on the Hill and Wicksteed fires yields results that further support our oxygen-limitation hypothesis. For these two fires, a regression of the CH_4 emission factor onto the ratio of CO to CO_2 emission factors yields a correlation coefficient (r) of 0.83 significant at the 98% confidence level. As is shown in Figure VII C3.2, the emissions data for Hill and Wicksteed clearly illustrate the increase in CH_4 emissions with increasing CO emissions that would be expected in an oxygen-limited environment.

Further evidence of oxygen-limitation occurring in biomass fires is given graphically in Figure VII C3.3, which shows CO/CO_2 and H_2 concentrations as a function of O_2 concentration for the relatively intense Battersby fire. This figure is reproduced from Hegg *et al.* (in press), and for a detailed discussion of the graphical analysis the reader is referred to the work of the aforementioned authors. In summary, however, Figure VII C3.3 shows that high concentrations of H_2 occur only when the amount of available O_2 is low, thus strengthening the conclusion that biomass fires are commonly oxygen-limited. At present, we are combining our airborne measurements of CO, CO_2 , and H_2 emissions for the Hill and Wicksteed fires with ground level measurements of O_2 concentrations in order to more fully examine – and hopefully substantiate – our contention regarding this interesting phenomena of oxygen-limitation in biomass fires.

Based on the data listed in Table VII C3.II, we obtain an estimated global flux of non-methane hydrocarbons (NMHC) from the fire emissions of $\sim 15 \text{ Tg yr}^{-1}$. This value

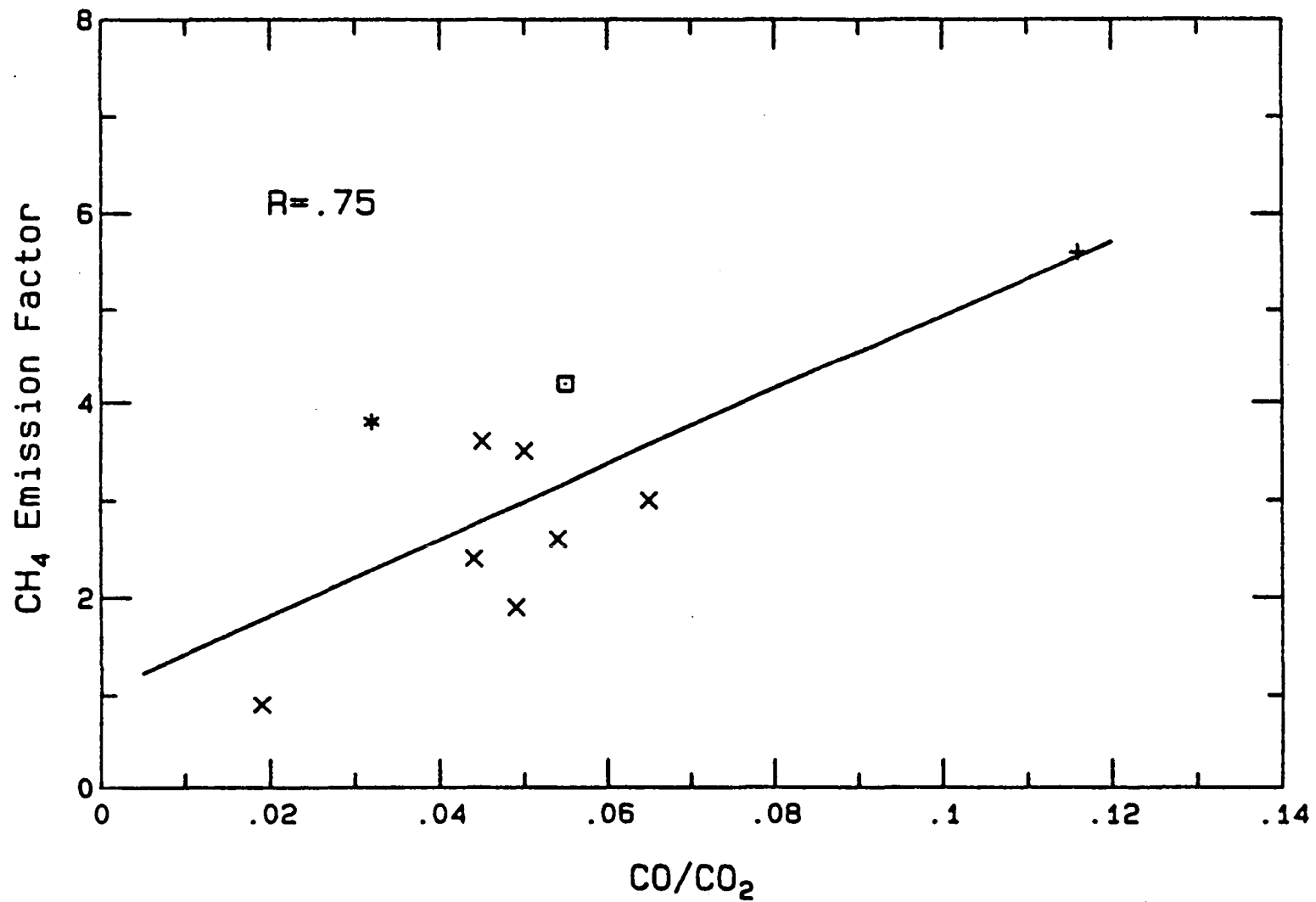


Figure VII C3.1 CH₄ emission factor versus ratio of CO to CO₂ emission factors for the ten fires studied. Symbols used represent the following: Battersby (+), Hill (square), Hornepayne (*), Other fires (x). R is the correlation coefficient, and the line shown is a linear regression (see text).

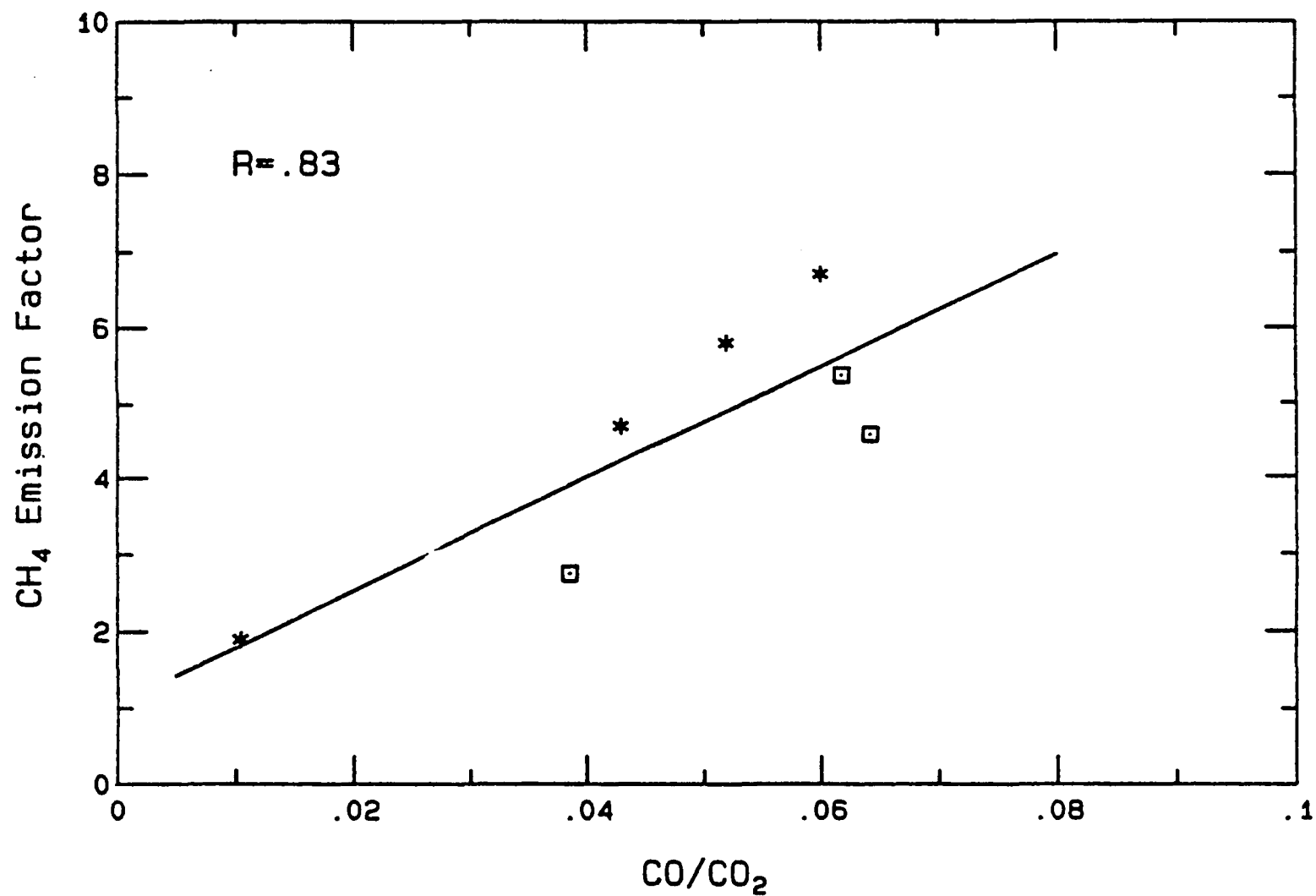


Figure VII C3.2 CH₄ emission factor versus ratio of CO to CO₂ emission factors for Hill (square) and Hornepayne (*). R is the correlation coefficient, and the line shown is a linear regression (see text).

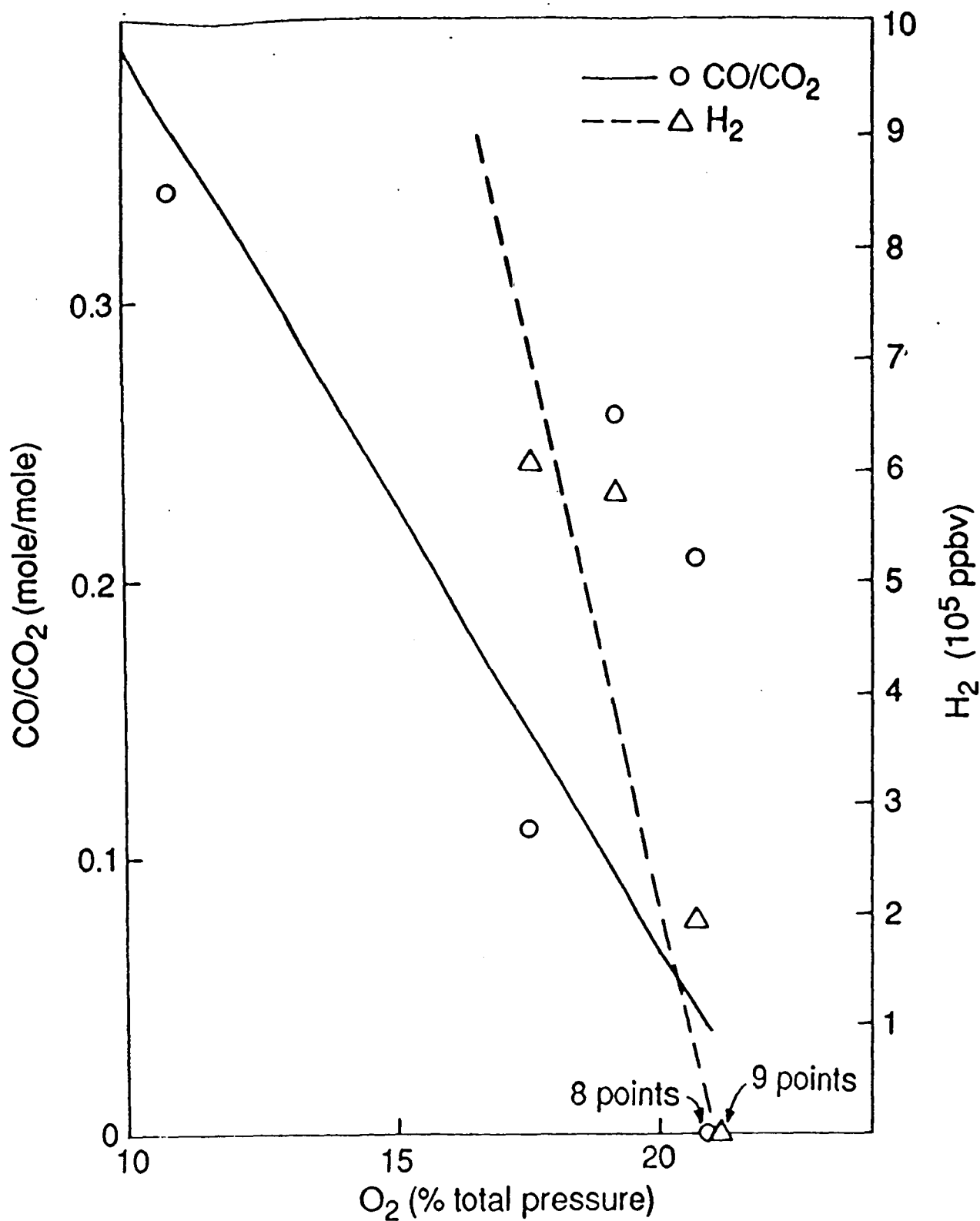


Figure VII C3.3 Concentration ratio of CO/CO₂ (circles) and H₂ concentration (triangle) versus O₂ in the plume from the Battersby fire. The data were obtained at or within 100 m of the ground. The lines shown are linear regressions (see text).

we feel is in reasonable agreement with the result of 30 Tg yr^{-1} obtained by Crutzen *et al.* (1985), due to the fact that only a portion of all the NMHC's have been incorporated into our data set.

Measurements of N_2O emission from combustion sources have recently come under scrutiny due to the discovery of an artifact in the use of sampling containers. Muzio and Kramlich (1988) have found that the storage of moist combustion products containing SO_2 and NO for relatively short periods can stimulate the production of high concentrations (on the order of several hundred ppm) of N_2O in containers which previously contained no N_2O . Our trace gas emissions are based on steel canister samples. We do not, however, feel our N_2O measurements are artifacts. The concentrations of SO_2 required for N_2O formation in the containers are at least three orders of magnitude larger than the SO_2 concentrations we measured in the plumes from the fires in this study (Muzio and Kramlich stated that SO_2 concentrations below 600 ppm resulted in negligible production of N_2O ; typical SO_2 concentrations we have measured are only on the order of 1-15 ppb). We therefore contend that our emission values for N_2O are indicative of processes occurring within the plume.

The estimated global flux of N_2O shown in Table VII C3.II (2.4 Tg yr^{-1}) corresponds to an emission of $\sim 1.5 \text{ Tg N yr}^{-1}$. This value is in agreement with a previous estimate of 1.6 Tg N yr^{-1} by Crutzen *et al.* (1985). Furthermore, our emission flux of $2.4 \text{ Tg N}_2\text{O yr}^{-1}$ represents approximately 16% of the total worldwide flux of the species, thereby strengthening the contention that biomass burning contributes significantly to the atmospheric N_2O reservoir.

One persistent, unexpected and not completely explained feature of our biomass fires is the presence of freons in the smoke. Because F12 cannot be produced by fires, the presence of this trace gas in the smoke plume must be due to the resuspension of F12 that had been previously deposited onto the fuel bed (Hegg *et al.*, in press).

Our estimated flux of F12 from biomass burning (0.08 Tg yr^{-1}) represents a significant fraction (~20%) of the annual global emission of this species (this percentage value was calculated using the National Research Council (1983) emission estimate of $0.4 \text{ Tg F12 yr}^{-1}$). Our results therefore suggest that deposition of F12 may be significant globally. This hypothesis is contrary to the current belief that the only sink for F12 that is important in atmospheric budget calculations is loss by photo-disassociation in the stratosphere. While the actual method by which freons could be sequestered in biomass or soils is uncertain, we are confident that this result is not an artifact. We do, however, have some concern about the results from Lodi 1 which may be anomalous (see Table VII C3.I). These elevated emissions heavily influenced the average value of the F12/CO ratio used in calculating the flux of F12 due to biomass burning (for a detailed discussion of our concerns with the F12 emissions from the Lodi 1 fire, the reader is referred to the paper by Hegg et al. (in press)). However, a calculation of the global flux of F12 that omits the Lodi 1 fire emission measurements yields a value of 0.04 Tg yr^{-1} . This result is still a significant fraction (~10%) of the total global flux of F12, thus suggesting that deposition may indeed be an important sink for tropospheric F12.

In the case of the Hill and Wicksteed planned burns, the F12 emissions were either zero or very small (see Table VII C3.I). These results are, however, consistent with our contention regarding resuspension of previously deposited pollutants. The emission of such organic species as F12 is, in general, substantially higher in urban areas. Consequently, one would expect the amount of pollutants deposited on the vegetation in the surrounding areas to be relatively high. Because the Hill and Wicksteed fires took place in a rural environment, the vegetation consumed in the fires would be expected to contain markedly less F12 than is found on biomass in urban settings. The F12 emissions would, therefore, be predicted to be extremely low (versus the elevated emissions from the Lodi 1 and Lodi 2 fires). This conjecture is verified by our results.

As is shown in Table VII C3.II our estimated flux of NO_x from fire emissions is 56 Tg yr^{-1} . This value corresponds to $\sim 19 \text{ Tg N yr}^{-1}$ (Hegg *et al.*, in press). By comparison, a previous estimate of the global flux of NO_x due to biomass burning yielded a value of 12 Tg N yr^{-1} with a range of $4 - 24 \text{ Tg N yr}^{-1}$ (Logan, 1983). Even though our estimate of 19 Tg N yr^{-1} falls within Logan's wide range, our emission value nevertheless suggests that the flux of NO_x from fire emissions may be more important than was earlier assumed. Further evidence for the greater impact of biomass burning on the worldwide flux of NO_x arises from the fact that our estimated flux value is $\sim 40\%$ of the total NO_x emissions. This result indicates that NO_x emissions from fires are comparable to emissions of this species from fossil fuel combustion (c.f. Crutzen *et al.*, 1979; Logan, 1983).

The high emission of NO_x from biomass burning may be due to the revolatilization of NO_x that had been previously deposited on the fuel bed (for a complete discussion of this process, the reader is referred to Hegg *et al.* (1988) and Hegg *et al.* (in press)). Consequently, we contend that resuspension by biomass burning of previously deposited NO_x should be included in the formulation of global flux estimates.

We were unable to retrieve any useful NO_x data at the Hill fire due to sensor saturation problems. The data from Wicksteed looks more promising and preliminary estimates indicate an average NO_x emission factor on the order of 1.0 g/kg . Further analysis is needed to arrive at a more accurate figure

Summary

Using measurements of trace gas emissions from ten biomass fires, estimates have been made as to the contribution of fire emissions to the global fluxes of various trace gas species. For certain gases (e.g., CH_4 , NMHC, and N_2O), our results agree favorably with previous estimates. However, our results for the estimated fluxes of NH_3 , NO_x , and F12 are noticeably higher than earlier results. The increased NO_x and F12 emissions may be the result of resuspension of previously deposited pollutants. Consequently, the impact of

fire emissions on the atmospheric reservoirs of NO_x and F12 – as well as NH_3 – may need to be re-assessed.

Our results also indicate that biomass fires may, to some degree, be oxygen-limited. As a result, larger amounts of such saturated hydrocarbon species as CH_4 may be produced. Emissions data for the relatively intense Battersby fire have proven to be highly consistent with the oxygen-limitation hypothesis. A preliminary study of the Hill and Wicksteed planned burns has also yielded results supporting our contention, and with further analysis of the emissions from these two fires we hope to solidify our understanding of the phenomena of oxygen-limitation in biomass fires.

VII.D. COMMENTS ON THE CLOUD PHYSICS OF THE HILL AND WICKSTEED CAPPING CUMULUS CLOUDS

The University of Washington's Convair C131A is well equipped as a cloud physics aircraft (see Appendix A) and as a part of our scavenging experiment some cloud physics data was obtained. See Section II for a discussion of the day's meteorology.

The Hill Thunderstorm -

At the time of the Hill fire ignition, the boundary layer was capped by a scattered field of cumulus mediocris in the area of the fire site. The fire plume was immediately capped with a cumulus cloud whose top soared rapidly to 7-8 km. We noted that precipitation in the form of small hail and rain developed abnormally early in the cumulus life cycle. However, aside from the smoke, the cloud was otherwise normal in appearance and typical of a cumulus development which is fixed geographically due to heat release or orography. The buoyant column of hot, moist air bent, in modest shear, above the fire until it became unstable forming a new ascending bubble and thereby forcing still another cumulus. While these convective bubbles remained active aloft from latent heat release, they quickly became disorganized at their bases when they moved downwind from the fire. The capping cumulus and several of the downwind drifting cumulus clouds produced precipitation for much of the afternoon (our own observations in conjunction with the lightning discharge map indicate that one or more of the fire spawned cumulonimbus clouds achieved an independent existence continuing to produce precipitation far downwind).

The droplet and hydrometeor size distributions are surprisingly normal. Figure VII.D.1 describes a sample taken in the ascending smoke column which was intended to be below the condensation level, but instead contained some of the cloud's earliest condensation. Hot wire measurements of liquid water content (LWC) ($\leq 60\mu\text{m}$ diameter)

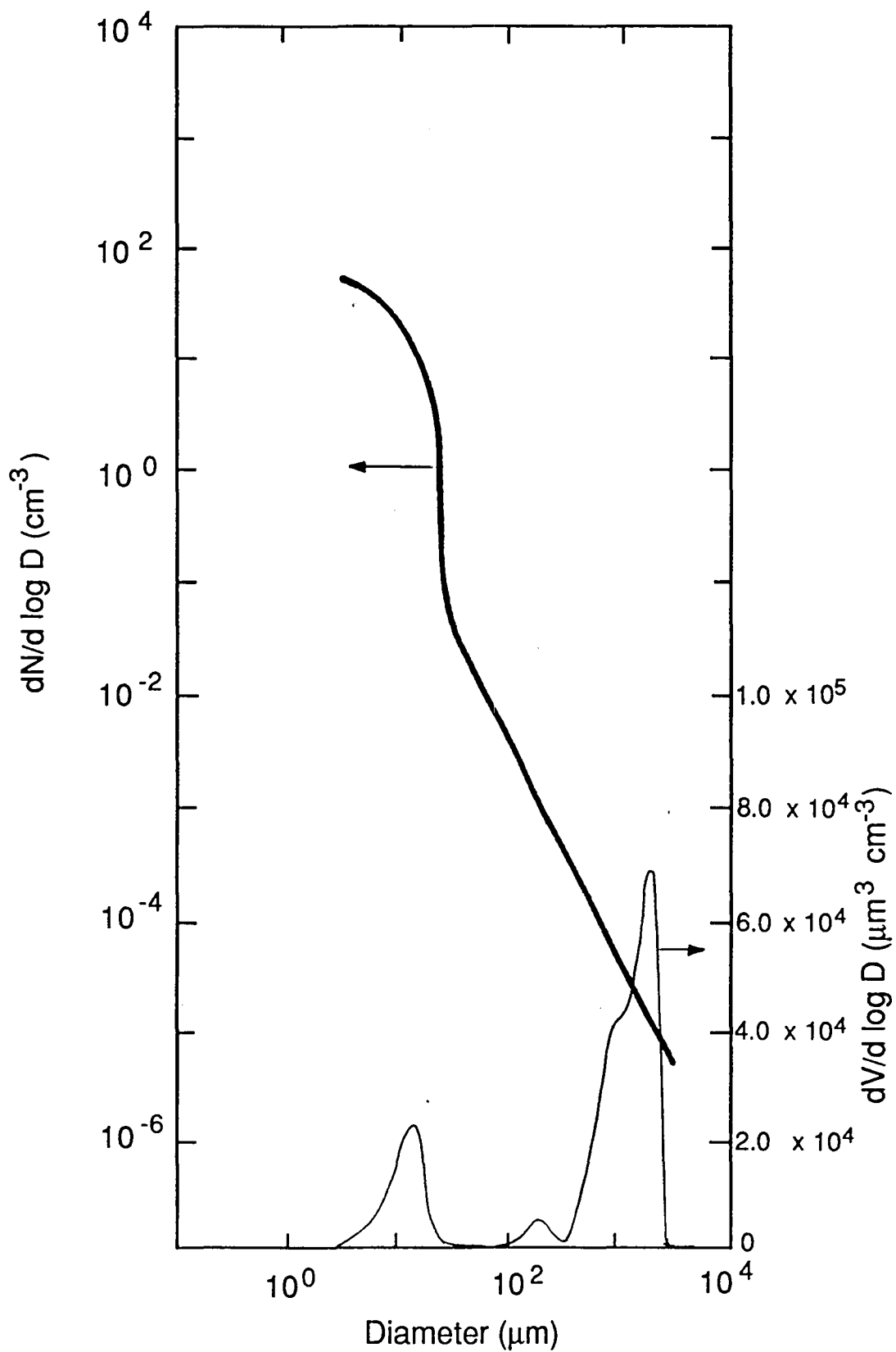


Figure VII D.1 Droplet number and volume spectra at 1430 LDT near cloud base in the ascending smoke column at the Hill fire.

show peak concentrations of only 0.25 gm^{-3} . Droplet number concentrations are similarly low; however there are already many precipitation sized particles present. From a cloud physics standpoint this would be inexplicable in a weakly sheared free-convection cumulonimbus at this phase in its development, and, in fact, it is not precipitation. In Figure. VII.D.2 we see laser camera images (selected from a later time, but similar to that found at 1430 LDT) of the precipitation size particles. These particles are ash and soil debris and while visually they could be unusual ice particle forms, this hypothesis is rejected because the optical ice particle counter fails to identify them as ice.

At 1437 LDT we again penetrate the cloud, this time $\sim 80 \text{ m}$ higher (we spent most of the previous five minutes picking up scattered small objects – pencils, cups, cookies, etc. which were not properly stowed) and now the liquid water content is $\sim 1 \text{ gm}^{-3}$ and the droplet concentration is up an order of magnitude (see Fig. VII.D.3). The droplet number mode has now shifted from the edge of resolution ($\sim 3 \mu\text{m}$) to greater than $10 \mu\text{m}$, while the mass mode has essentially remained in place. Some of the millimeter sized particles may be precipitation!

Next we move slightly downwind penetrating the cumulus which has partially detached from the fire's ascending smoke column. Precipitation is visually apparent beneath the cloud base. Figure VII.D.4 shows the precipitation tail in the droplet size distribution at 1454 LDT. A second droplet mode at $\sim 30 \mu\text{m}$ is also in evidence. The pass was noisy in the aircraft with the rattle of small hail shown as imaged by the laser camera in Figure VII.D.5. Shortly after this a few snowflakes are imaged as well (Fig. VII.D.6). Thus we saw the cloud microphysics which would be normal for a cumulonimbus in terms of cloud droplet and liquid water content with only the rapid onset of precipitation – rain, hail and snow – being unusual.

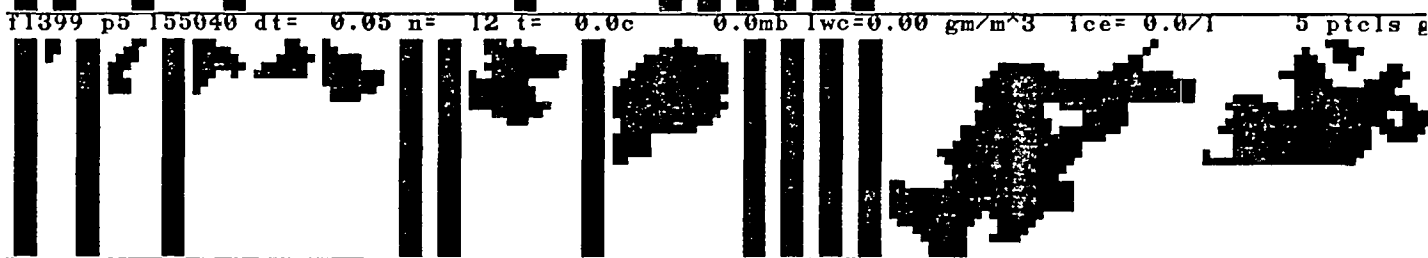
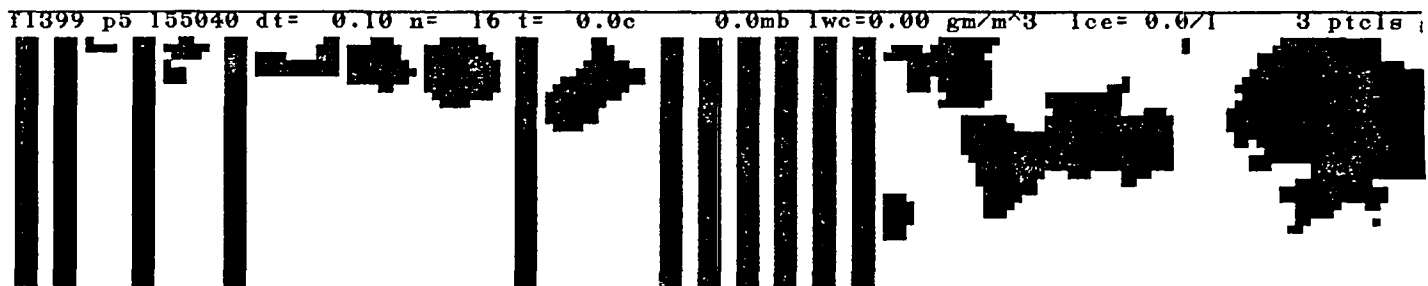
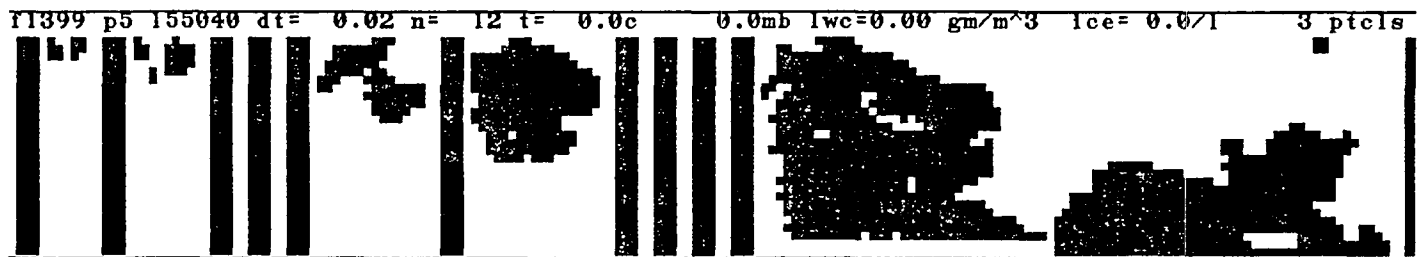


Figure VII D.2. Laser camera images of ultra-giant ash and soil particles from the Hill fire.

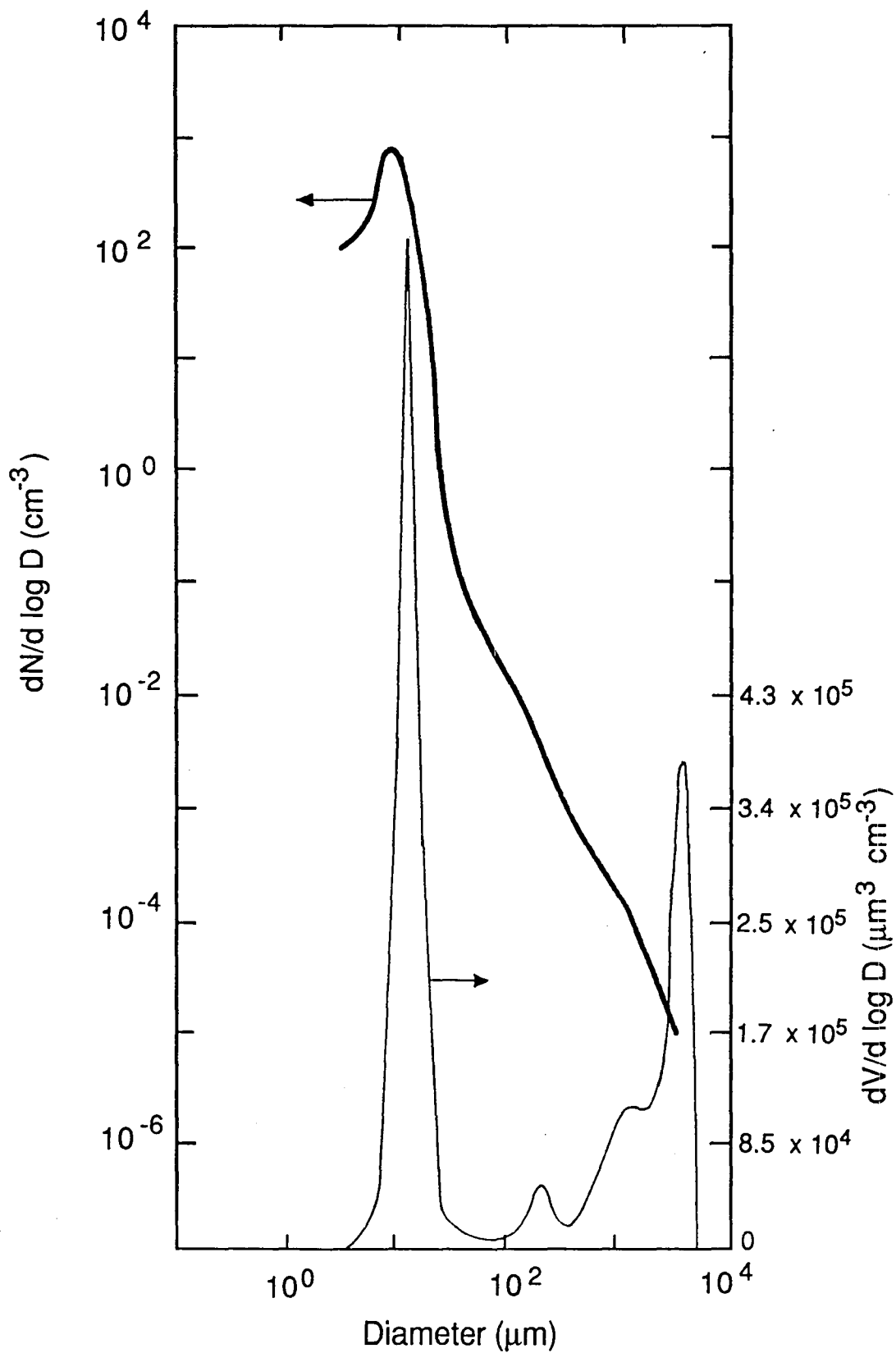


Figure VII D.3 Droplet number and volume spectra at 1437 LDT approximately 100 m above cloud base at the Hill fire.

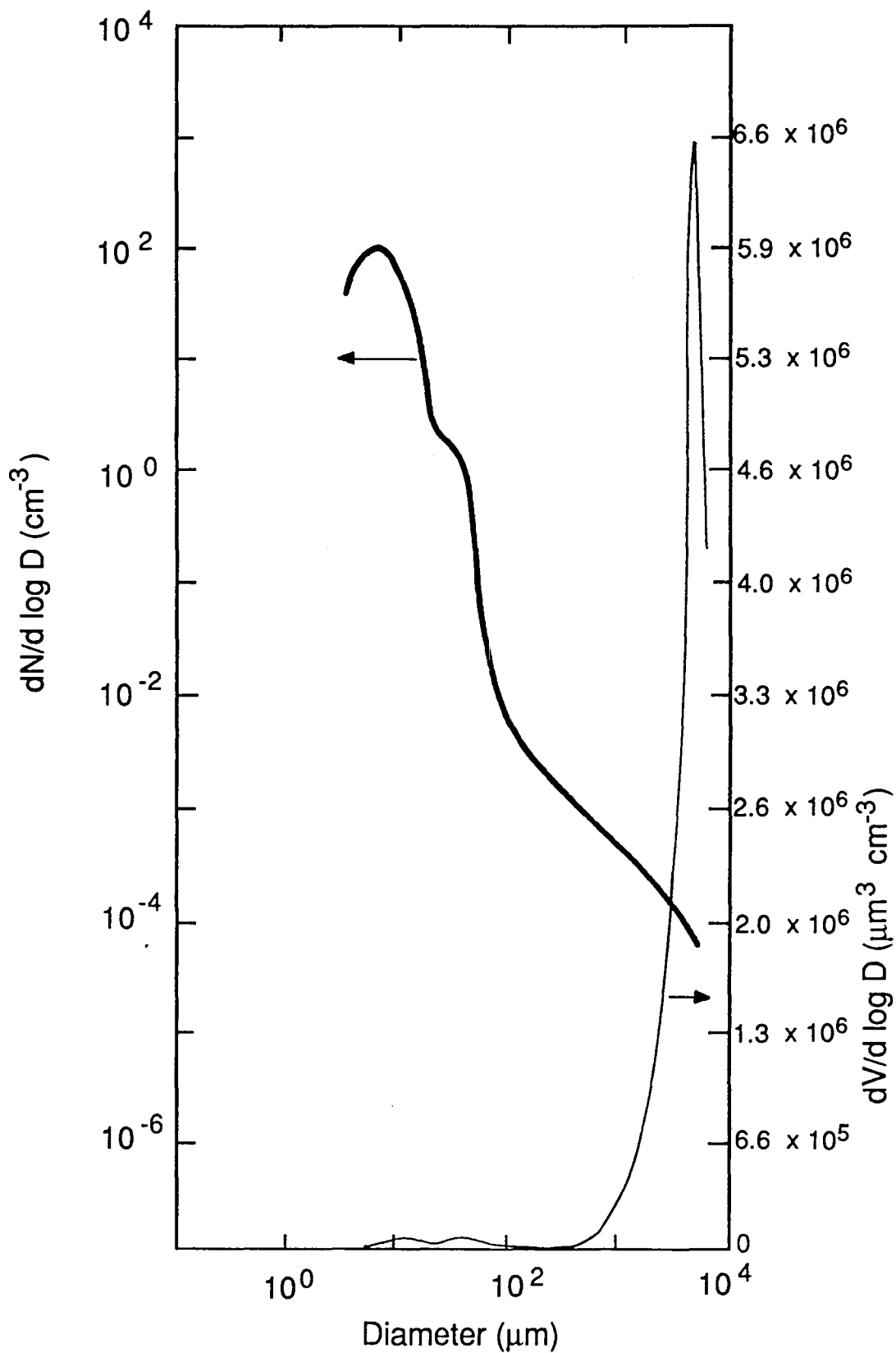


Figure VII D.4 Droplet number and volume spectra at 1454 LDT in precipitating region downwind of the Hill fire.

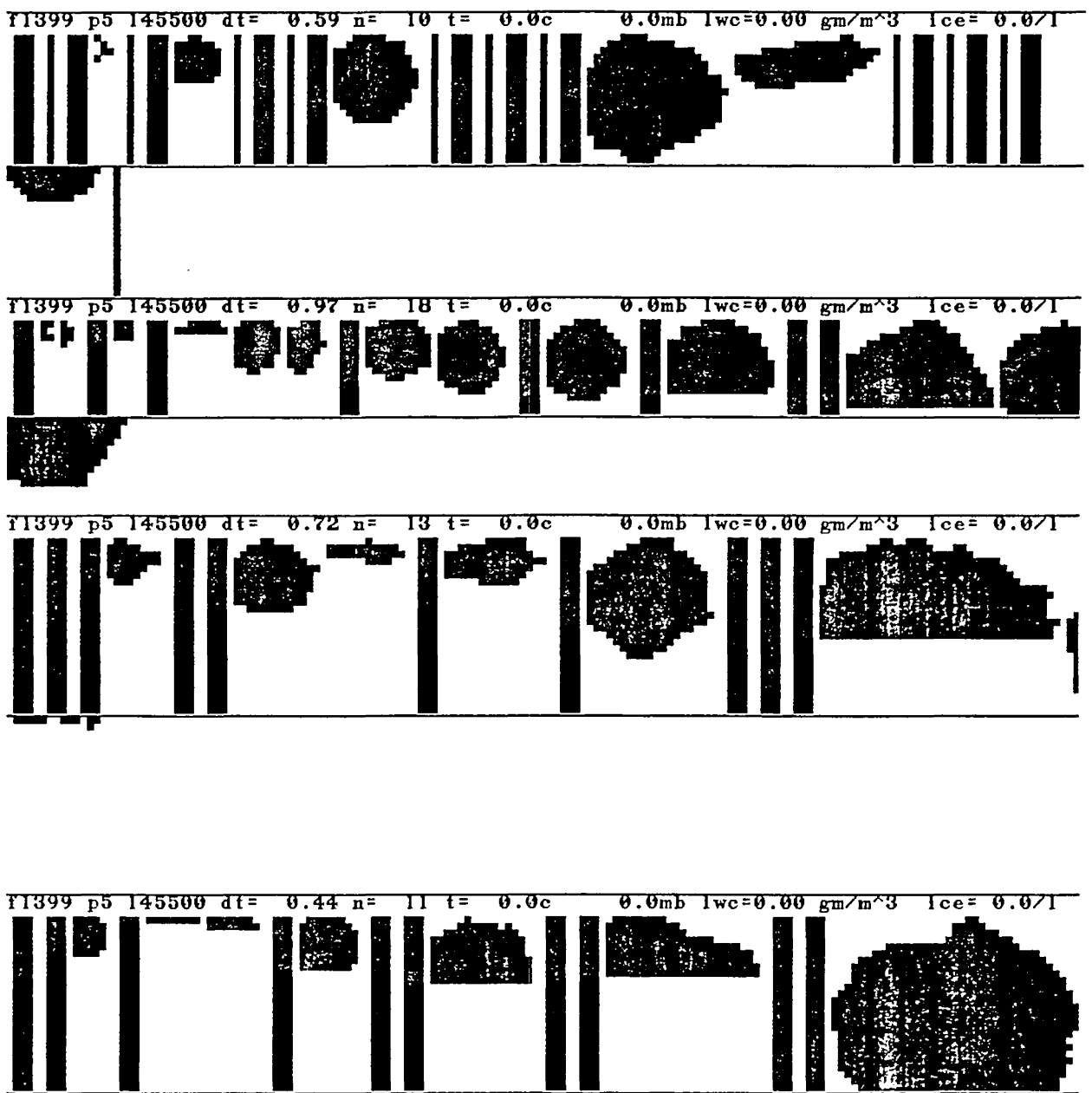


Figure VII D.5. Laser camera images of small hail early (1454 LDT) in the Hill fire's cumulus cloud. The vertical bars are 3200 μm high.

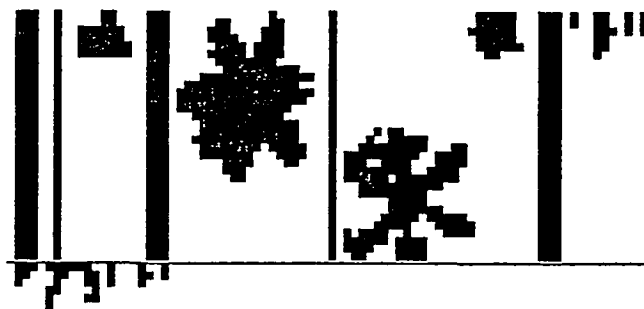


Figure VII D.6. Typical snowfall imaged by the laser cameras downwind of the Hill fire towering cumulus cloud. The vertical bars are 3200 μm .

The Wicksteed Cumulonimbus -

Meteorologically the two experimental days were extremely similar and the fire capping cumulus were also grossly similar in size, cloud base elevation and cloud top height. Yet it was our immediate impression that the clouds were very different. Hill's cumulonimbus simply seemed to ingest all of the smoke from the fire, and its cloud base smoke mass concentrations were higher, yet its total smoke flux now seems lower.

A major difference was that the Wicksteed cumulonimbus was smaller than the ascending smoke column, evidently capping only a hotter core of the column. Consequently, there was smoke everywhere at cloud base elevation and our overall impression was of lower total scavenging (contrarily, Section VII.F notes that for at least a time the cloud and precipitation scavenging efficiency was actually highest at Wicksteed). Precipitation at Wicksteed also took longer to develop, showers were less intense and not continuous, and no lightning was observed either on board or by the Ontario "LL" system. The sequence of droplet size distributions (Figs. VII.D.7 to VII.D.10) were selected to illustrate a similar sequence as at Hill. Figure VII.D.7 is at 760 mb, about 500 m higher than VII.D.1, and both droplet concentration and liquid water content are higher. The droplet number mode is $\sim 8 \mu\text{m}$ diameter and similar concentrations of millimeter sized particles (ash) are present. The next figure (Fig. VII.D.8) five minutes later (1619 LDT) shows a maturing droplet number mode ($\sim 10 \mu\text{m}$), rain and small hail.

The aircraft then pursued subcloud column samples for a period and when we returned to the cloud (1639 LDT) droplet liquid water remained identical ($\sim 0.75 \text{ gm}^{-3}$), but precipitation had largely stopped (Fig. VII.D.9) although the droplet number mode continued to grow slightly. Precipitation continued to be spotty and we used the FLIR to locate the cooler weak precipitation cores among the smoke extended downwind near cloud base. An example is shown in Figure VII.D.10.

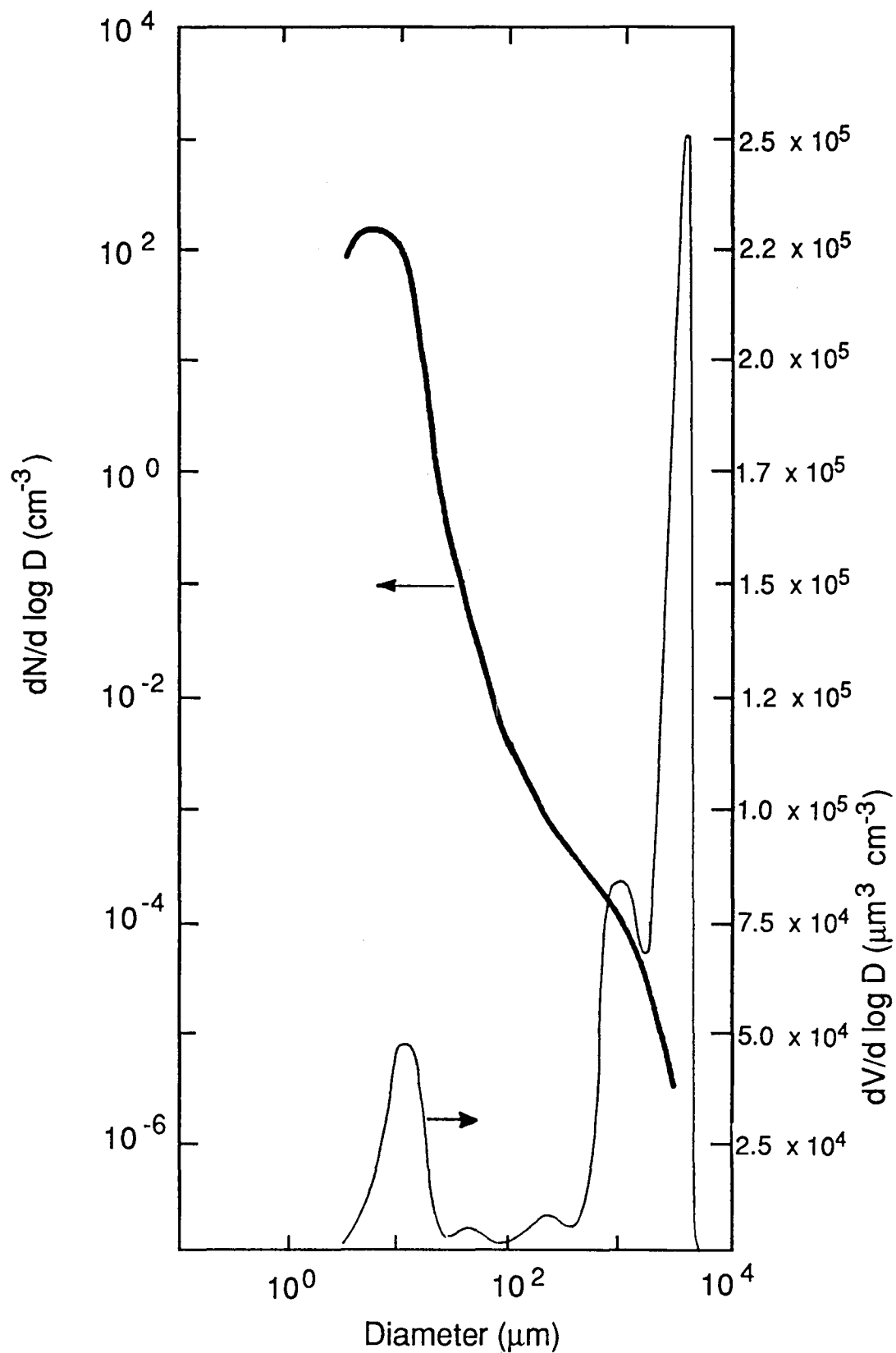


Figure VII D.7 Droplet number and volume spectra at 1614 LDT at the Wicksteed fire.

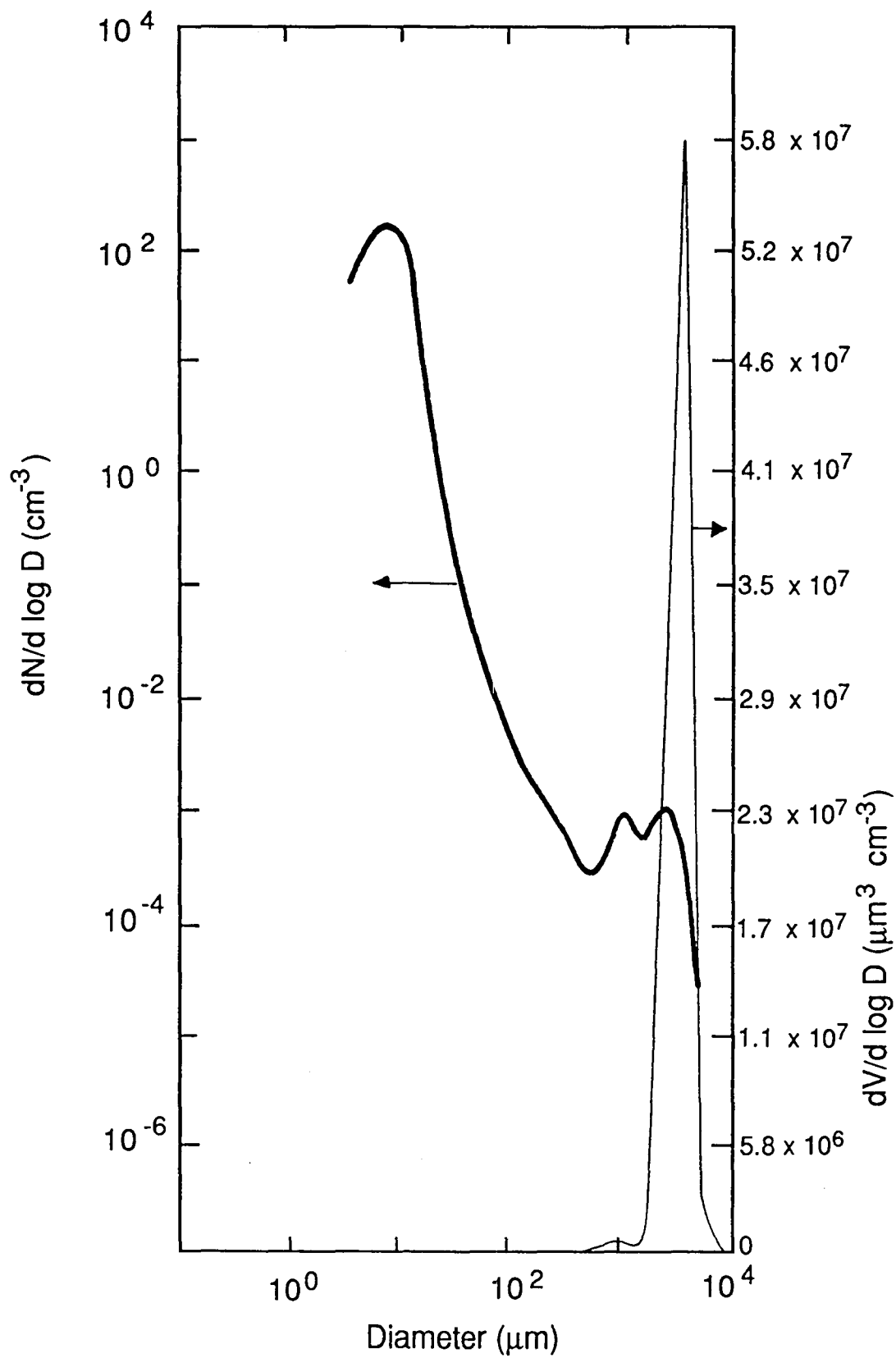


Figure VII D.8 Droplet number and volume spectra at 1619 LDT at the Wicksteed fire.

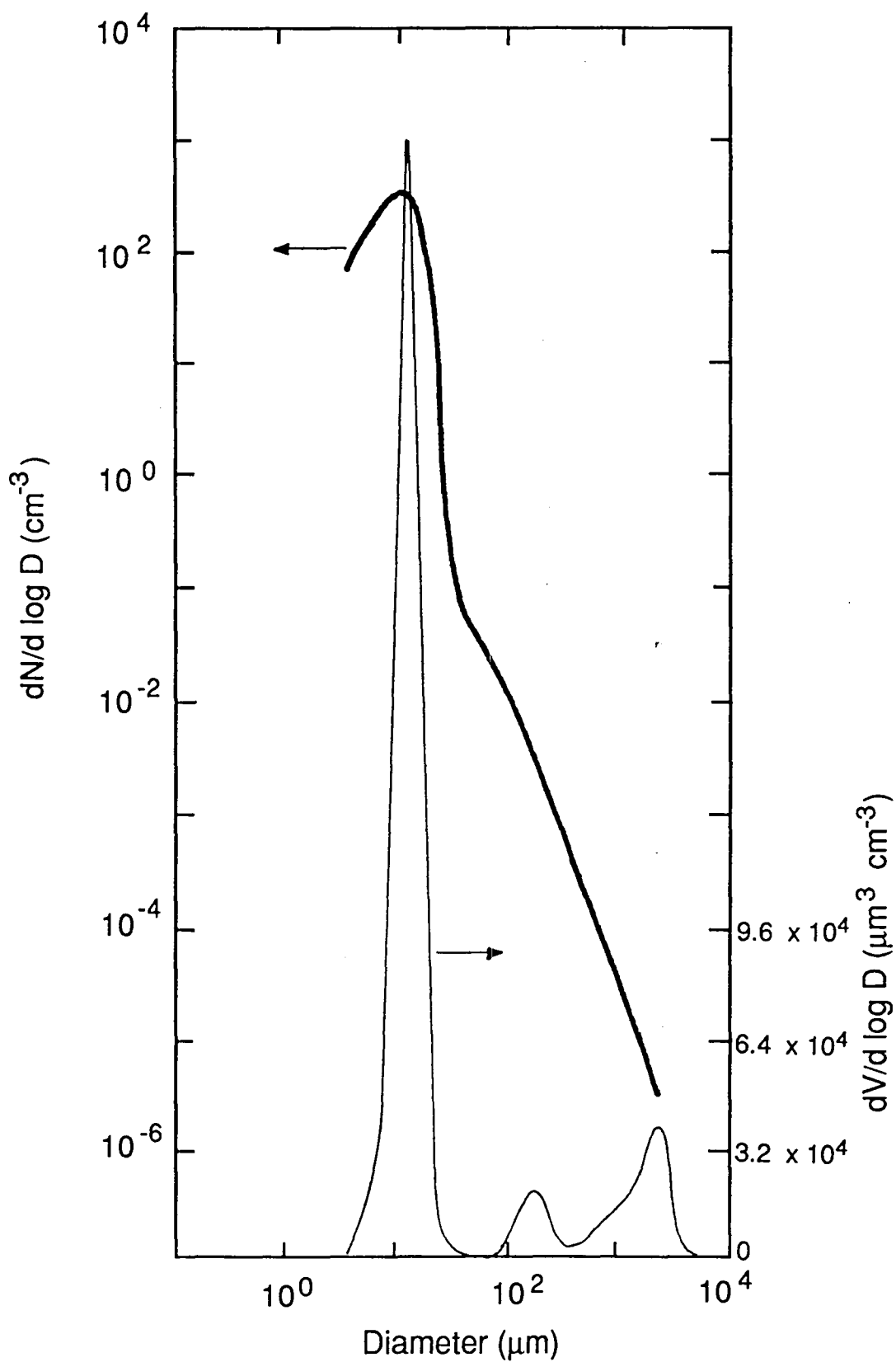


Figure VII D.9 Droplet number and volume spectra at 1639 LDT at the Wicksteed fire.

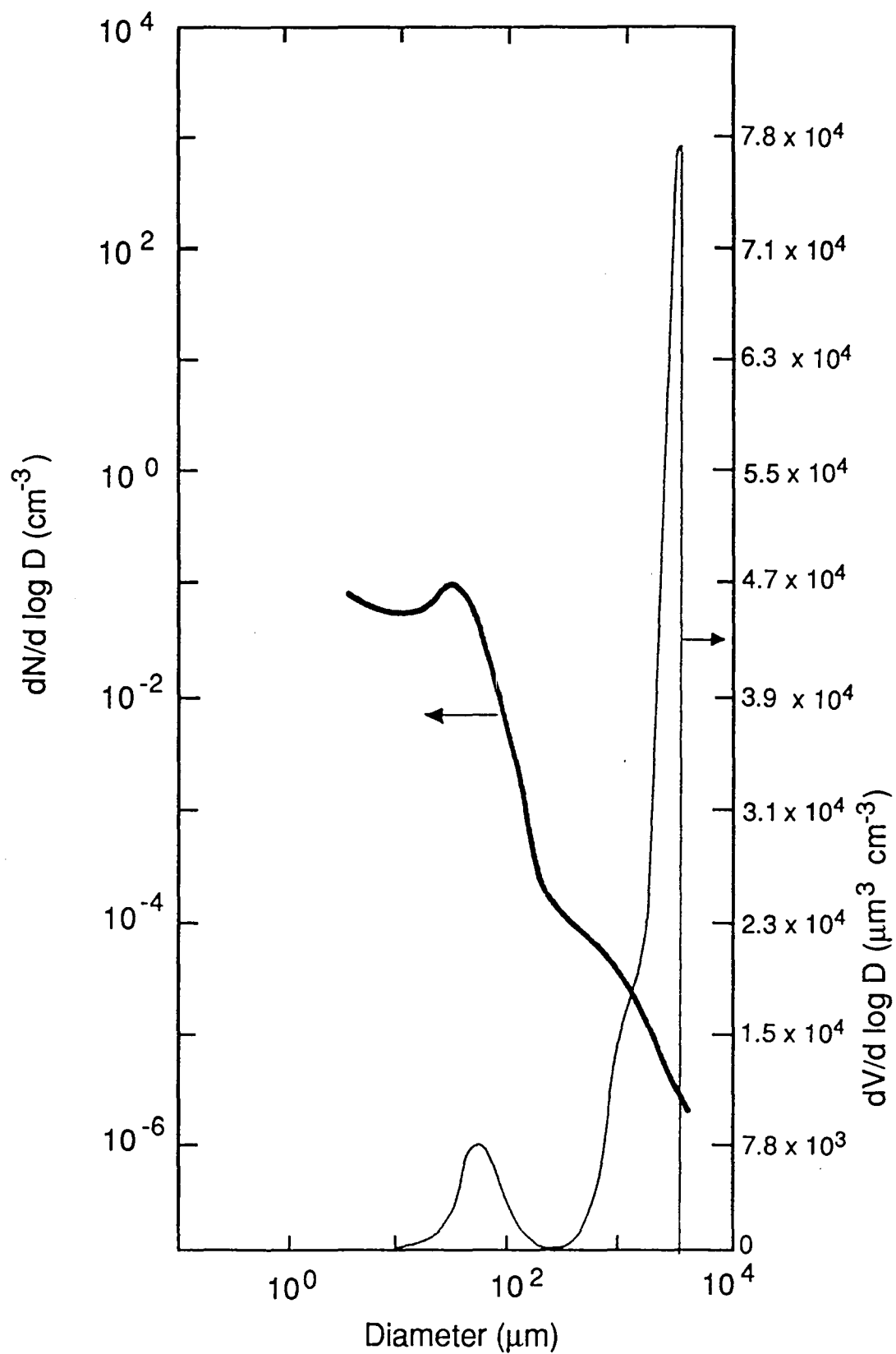


Figure VII D.10 Droplet number and volume spectra in a region of weak precipitation near cloud base downwind of the Wicksteed fire.

Summary

The primary feature of these fires which we should note is that both capping cumulus clouds managed significant precipitation which began rather rapidly compared to similar natural clouds.

We hypothesize that it is the presence, at cloud base, of large concentrations of large, giant and ultra-giant ash particles which allows the extremely rapid formation of precipitation despite the presence of very large fluxes of active cloud condensation nuclei (CCN) from the fire. Indeed some of the early discussions of prompt scavenging of fire capping cumulus suggested that the concentration of smoke CCN would divide the cloud's liquid water content between so many droplets that the warm rain collision/coalescence mechanism would be defeated. Thus little or no droplet aggregation would occur and since no rain would develop, no smoke particles would be precipitated to the ground. However, at this juncture it is clear that quite the opposite occurs. The large ash particles evidently act as collision/coalescence initiators allowing for precipitation to form far faster than normal. Similarly, since the formation of the ice phase is known to be greatly enhanced by the presence of large droplets, this very efficient precipitation mechanism also appears to be enhanced.

In all respects the fire capped cumulonimbus appears to be an efficient precipitation system. We suspect that many people in the weather modification field would be pleased with similar results.

VII.E. OPTICAL PROPERTIES OF SMOKE

Introduction

The optical properties of particles comprising smokes produced from biomass burning can be highly variable and depend on many factors including the type of fuel burned, the intensity of the fire, flame height, and the stage of combustion (McMahon, 1983; Patterson and McMahon, 1984). As fuel is consumed, biomass fires evolve through several stages in which particles of very different optical characteristics are produced. The chemical and physical description of these particles is that of a highly complex mixture of organic and inorganic material with a majority of the lofted aerosol mass contained in the submicron size range. In the early, flaming stages of combustion when high temperatures and oxygen deprivation prevail, conditions support pyrolytic production of particles consisting of high concentrations of both single spheres and sooty chains that are optically very absorbing. In the later, smoldering stages of combustion, smoke production is dominated by weakly or non absorbing liquid (waxy) and solid particles consisting of organic materials with a range of volatility in addition to non-sooty inorganic materials. Patterson and McMahon (1984) measured specific absorption on filter samples taken from laboratory fires of pine needles at various stages of combustion. They found a substantial increase in the production of elemental (or sooty) carbon in the flaming stage of combustion relative to the smoldering stage with the specific absorption coefficient ranging from $0.04 \text{ m}^2/\text{g}$ for the smoldering stage to about $1 \text{ m}^2/\text{g}$ for the flaming stage. These were measurements on smokes in a laboratory environment where burning conditions could be controlled. In large fires of several hectares or more the smokes likely consist of complex mixtures combining all combustion stages and domination by one or more phases at any given time and location.

The optical properties are usually described by the volume optical extinction coefficients, σ_e , σ_s , σ_a , where the subscripts indicate the form of extinction, 'e' for total

extinction, 's' for scattering and 'a' for absorption; the specific (or mass normalized) extinction, $B_i = \sigma_i/\rho$, where ρ is mass concentration and 'i' represents any of the extinction coefficients; and the albedo for single scattering, $\tilde{\omega}$ where $\tilde{\omega} = \sigma_s/\sigma_e$. The extinction coefficients depend on the complex refractive index of the particles, their size distribution and concentration. The specific extinction and the albedo for single scattering are normalized to concentration, however, and thus depend only on the fundamental chemical and physical properties of the particles. Specific scattering, $B_s = \sigma_s/\rho$, is not highly variable, normally ranging from about 3 to 4 m²/g (Waggoner and Weiss, 1981) for submicron aerosol. Specific absorption, however, is dependent on the relative content of elemental (or black) carbon comprising the particles and ranges from 0 m²/g for particles without any absorption to about 10 m²/g (ref) for submicron size particles of pure soot.

Knowing the spatial extent of these optical coefficients, particularly the absorption related properties, for various stages of fire evolution and atmospheric conditions is important to understanding the dynamic properties of the fire and the resulting impact of transported smoke on radiative transfer and visibility.

Data Collection and Processing

Measurement of the optical extinction properties of smokes, especially from an aircraft where smoke penetration times can be as short as 10 seconds, and the mass concentration may vary by 10³ during that period require instrumentation with short time response and high dynamic range. We have developed a unique system for aircraft 'in-situ' measurement of smoke optical properties that include instruments to measure σ_e and σ_s in real time with a time response of about 1 second. Absorption is determined by difference, $\sigma_e - \sigma_s$, and albedo for single scattering by ratio, σ_s/σ_e . Specific absorption is determined from the average absorption over a plume transect and the mass measured on a filter sample collected from that transect.

The principal component in the system is an optical extinction cell (OEC). The extinction coefficient, σ_e , is measured directly from the decrease in optical transmittance over a single path of the cell as smoke flows through the instrument. A multiwavelength, high resolution integrating nephelometer is used in parallel with the OEC to measure the optical scattering coefficient, σ_s . The instruments are integrated into a system that is micro-processor based and controlled from a lap-top computer. During plume penetration the aircraft operator can monitor the 'in-situ' measurements of σ_e , σ_s , σ_a , and $\tilde{\omega}$ on a video display.

The OEC is an enclosed, 6.4 meter path length photometer designed to measure the change in brightness of a regulated light source over a single pass of the cell. Measurements are made at a wavelength of 540 nm. An initial brightness measurement is taken of reference (clear) air, I , and compared continuously to lamp brightness with sample air flowing through the cell, I . A reference light path is used to normalize all light measurements to constant lamp brightness. For smoke plume measurements, I_0 is determined from the air prior to entering the plume so that the change in transmittance in the plume is due to fire smoke only and not background aerosol. The extinction coefficient, σ_e , is calculated continuously from,

$$\sigma_e = 1/L \cdot \log_e (I_0/I)$$

where 'L' is the length of the cell. In the aircraft, flow is supplied by ram air through an isokinetic probe installed through the forward cabin wall. Near the entrance to the OEC, the flow is split to provide parallel flow to the nephelometer. The air exchange rate of each instrument is matched with adjustable gate valves located in the flow stream. Aerosol exchange rate in the OEC is several times per second. Data from the instruments is averaged over intervals of 0.5 seconds and then stored in both the lap top computer used by the operator and on the aircraft data acquisition system. A diagram of the system is shown

in Figure VII E.1. Pre-flight calibration of the nephelometer/OEC system is tested by measuring the ratio of coefficients determined from each instrument, $\tilde{\omega}$, for laboratory generated non-absorbing aerosol such as polyethylene glycol, NaCl or $(\text{NH}_4)_2\text{SO}_4$ while ensuring that the ratio is 1 for an appropriate size distribution. The system has been used successfully in several studies of prescribed biomass burns and wild fires beginning at the end of 1986 with the Lodi fires in Southern California (Weiss and Radke, 1987).

Results

The summarized results of aircraft measurements from two prescribed burns prior to the Hill and Wicksteed fires in Ontario are shown in Figure VII E.2 and in Table VIIA2.3. The two fires are the Troy, MT fire (October 8, 1987) and the Mabel Lake fire near Kelowna, B.C. (September 25, 1989). Both were small fires, 70 and 29 hectares respectively, of downed debris consisting of mixed wood types in which there was intense burning in the initial stages of combustion and relatively uncomplicated meteorological conditions. In both fires the aerosol was optically dark during the early stages of intense burning and became less dark as the fires progressed to a predominantly smoldering stage. This result is shown in the time series plots of $\tilde{\omega}$ (Fig. VII E.2) where the single scattering albedo measured at altitudes of 2 to 2.5 km was initially less than 0.7 in both fires and approached a relatively stable value in the smoke of about 0.9 during smoldering stages. Mean values of specific absorption for both fires were approximately $0.4 \text{ m}^2/\text{g}$ which is similar to the average values reported by Patterson and McMahon (1984).

These fires are relatively uncomplicated because of their size and low winds. Larger fires, however, such as Wicksteed and Hill can be more complicated to analyze because of simultaneous multiple phases contributing to the smoke and ensuing meteorological modification which include capping clouds, rain and hail. The fire at Hill produced relatively violent thunderstorm activity and was complicated to analyze. Wicksteed, however, was well structured and the optical measurements could be made in

Aircraft Flow System OEC-Nephelometer System

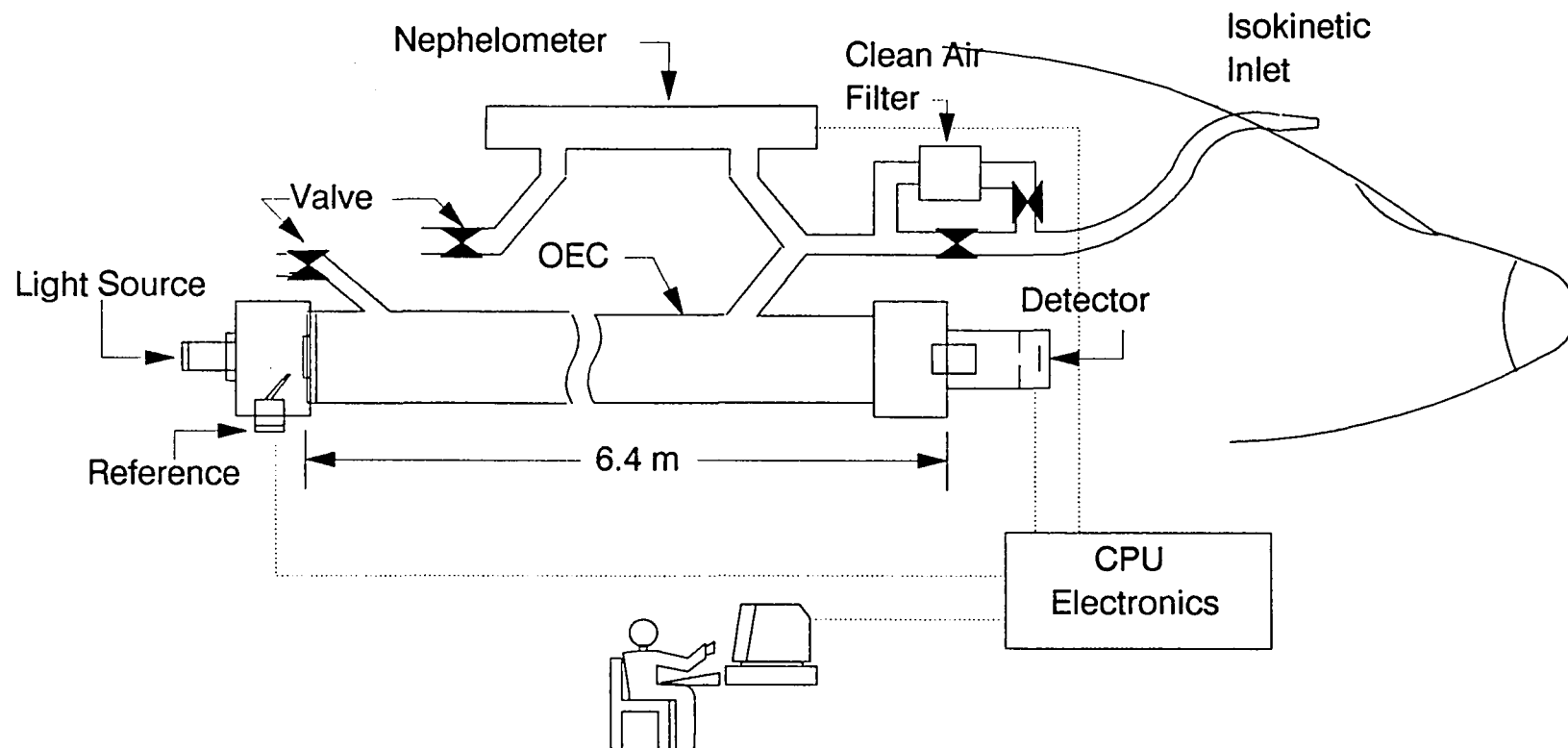
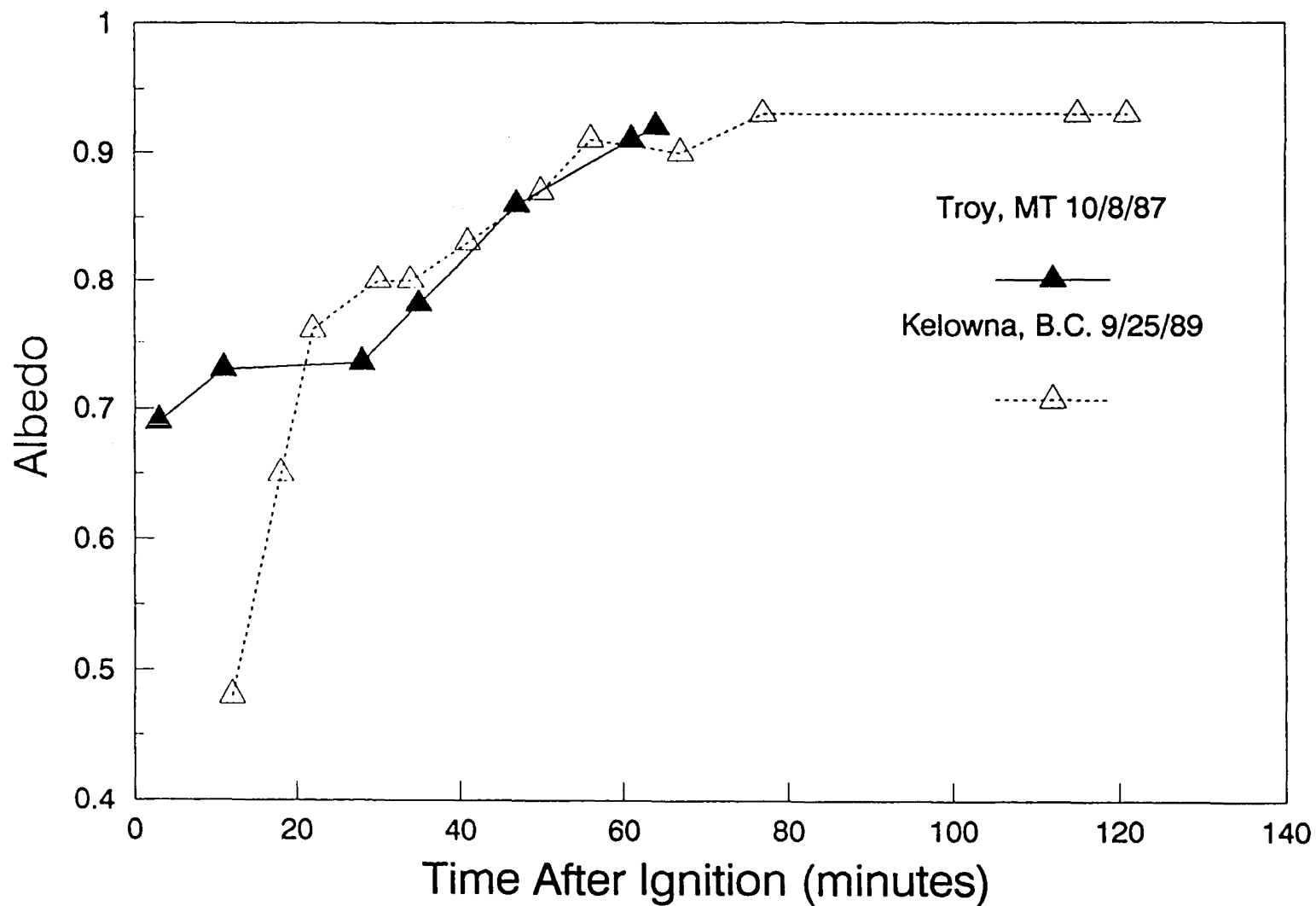


Figure VII E.1

Progression of Albedo after Fire Start



well defined phases of the smoke. Though Hill was burned prior to Wicksteed, they will be discussed in the reverse order because of the more sensible structure of Wicksteed.

Wicksteed Fire 8/12/89 -

The burn at Wicksteed encompassed 700 hectares of Herbicidal Birch, Poplar, and mixed Hardwoods. The fire was characterized by intense rapid combustion in the early stages, producing a column of very dark appearing smoke. A capping cumulus quickly developed above the column core and eventually extended to about 7000 m. Much of the rising column smoke was ingested by the capping cloud and appeared to quickly detrain. The remaining smoke and much of the very earliest smoke was carried downwind, near cloud base without passing through any cloud. The smoke column, capping cumulus cloud, and detraining smoke were fairly well defined and we were able to sample each of these attributes with reasonable independence from the other.

Optical measurements were made over a two hour period with the first observations directly in the column, just minutes after the initial ignition. In Figure VII E.3 is a rendition of the principal components of the smoke and resulting cloud. The letters in the figure show the approximate locations of plume transects where optical parameters were measured. The actual letters correspond to the letters associated with Figures VII E.4-8 and identify the optical extinction profiles for each of these transects. The upper edge of the solid curve in each profile indicates the total extinction coefficient, σ_e , as function of time, and the upper edge of the hatched curve represents the coefficients for scattering extinction, σ_s ; absorption is determined from the difference. The albedo listed in each figure is computed from the ratio of the areas under each extinction curve, or the average for the plume cross section.

The first measurements were made in the column (A,B in Fig. VII E.3) shortly after the initial ignition. The sampling protocol then progressed to measure detraining smoke in several transects (C,E,F,G,H,I,J,K,L), a few of which may have included some cloud.

HORNEPAYNE 8/12/89

Location of Optical Measurements

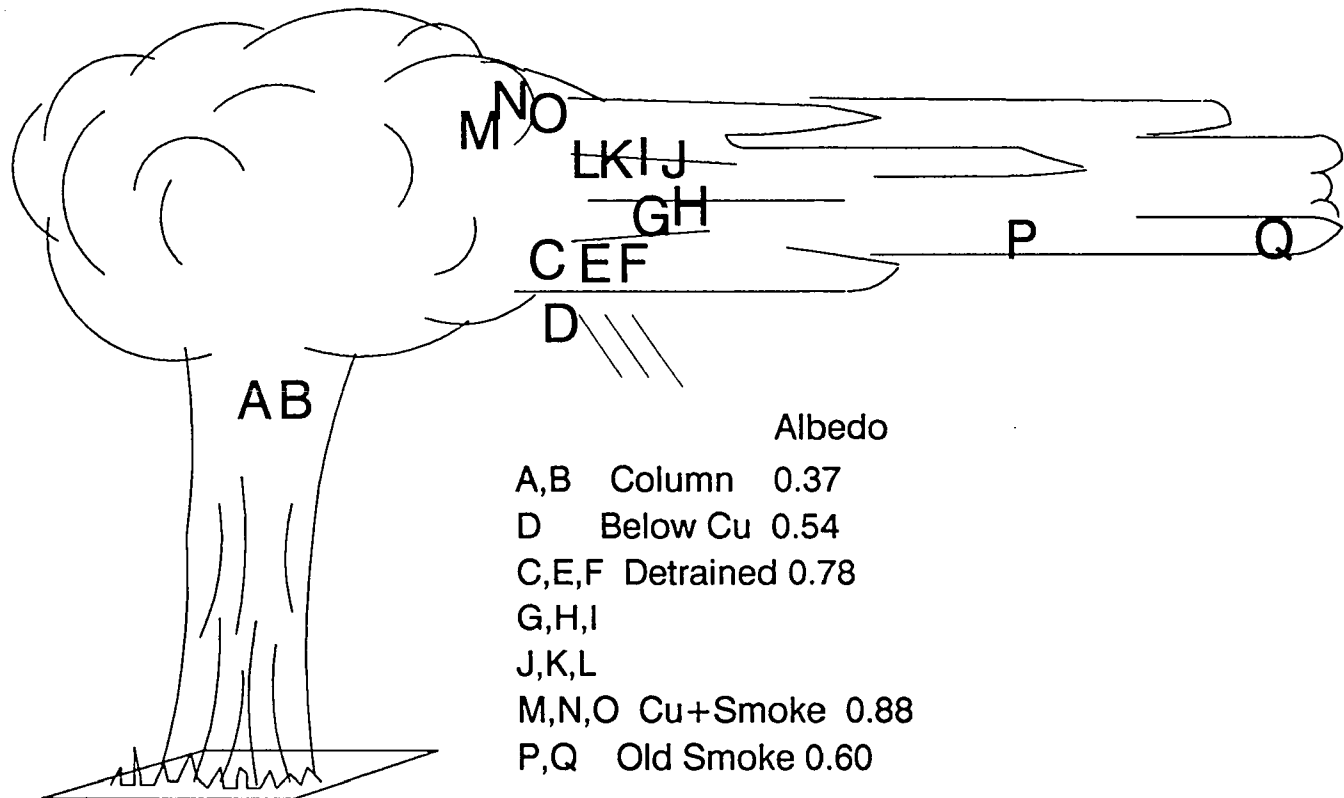
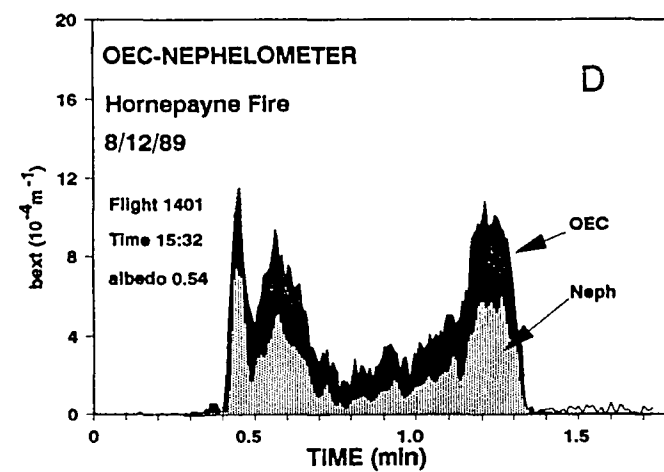
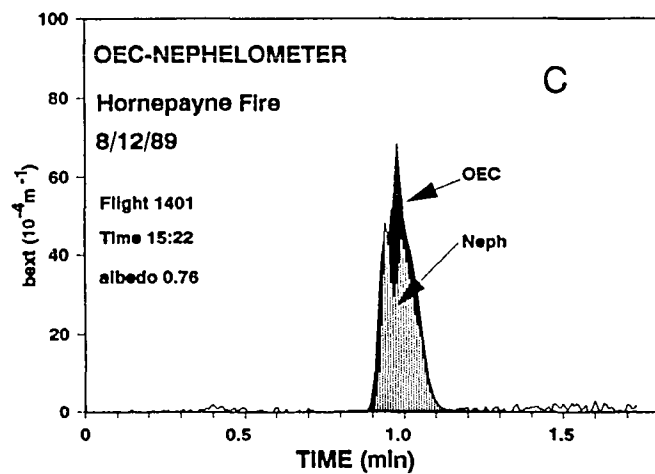
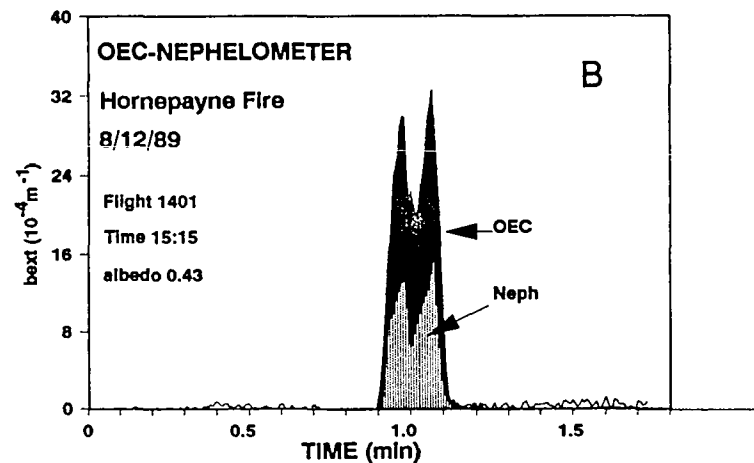
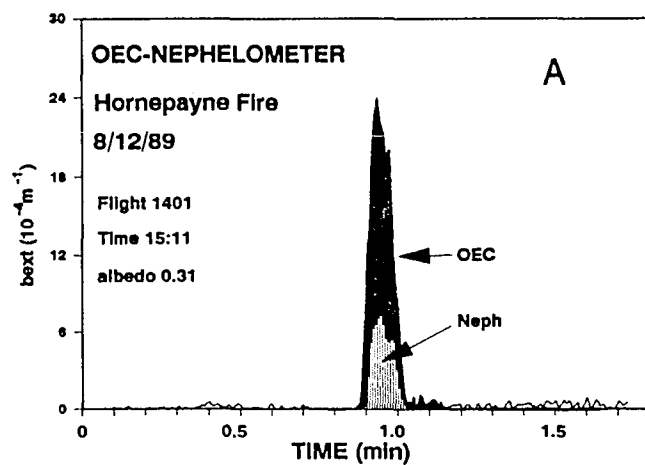
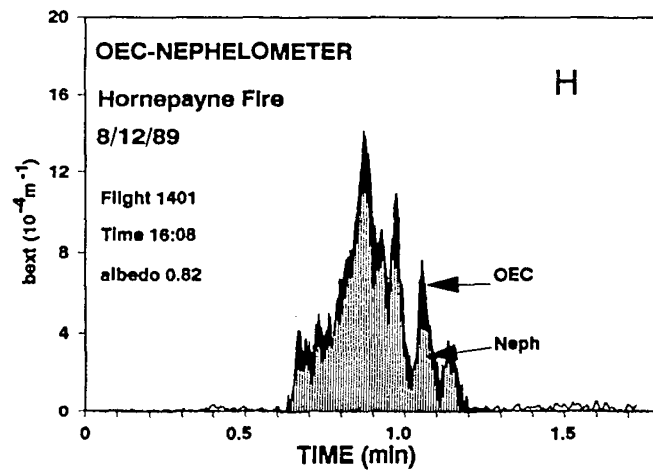
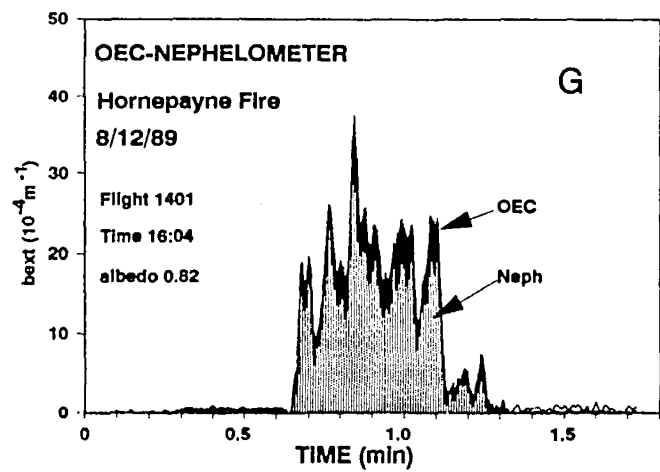
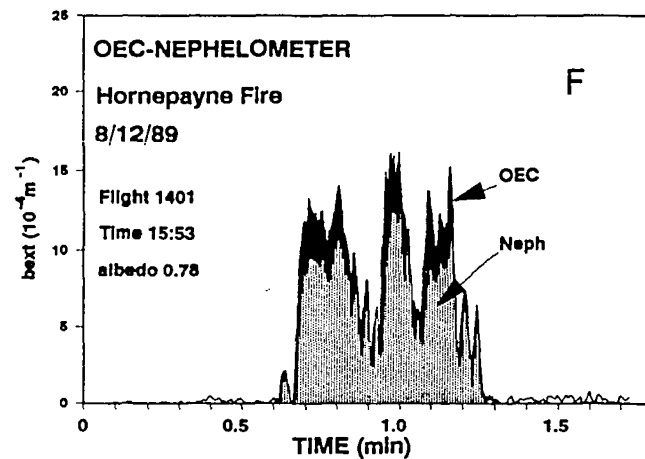
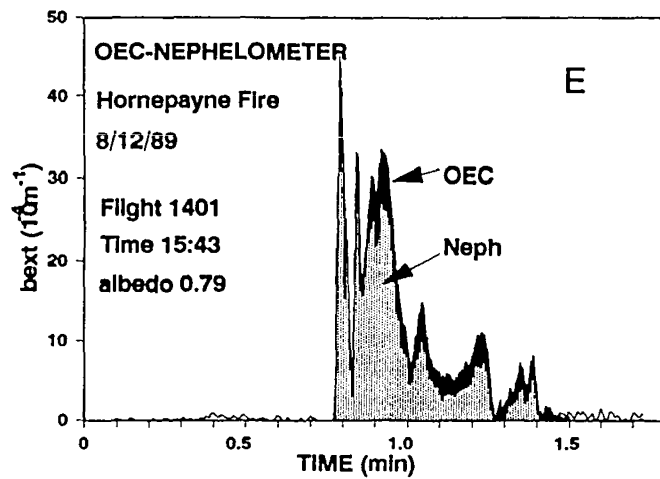


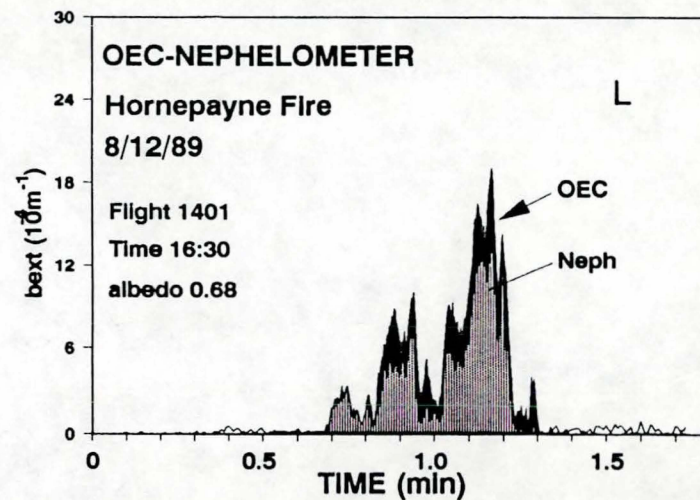
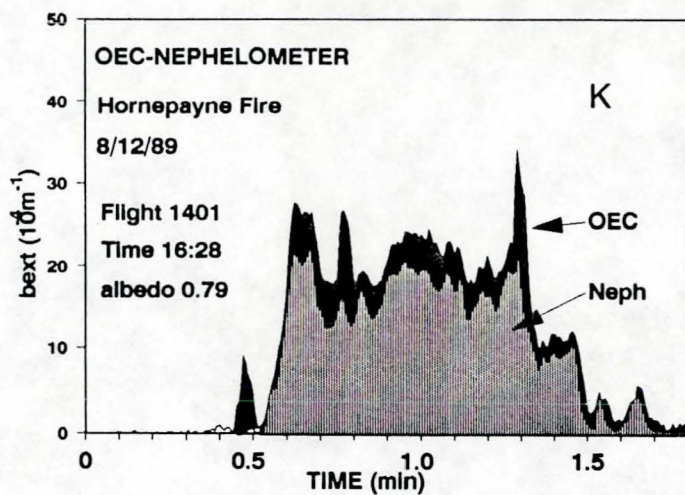
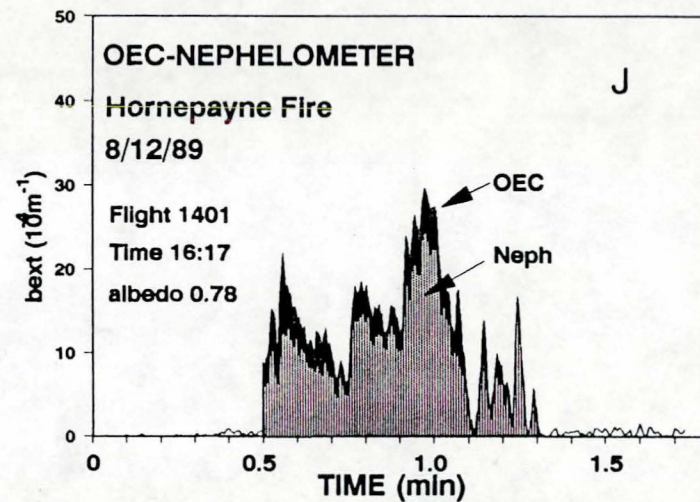
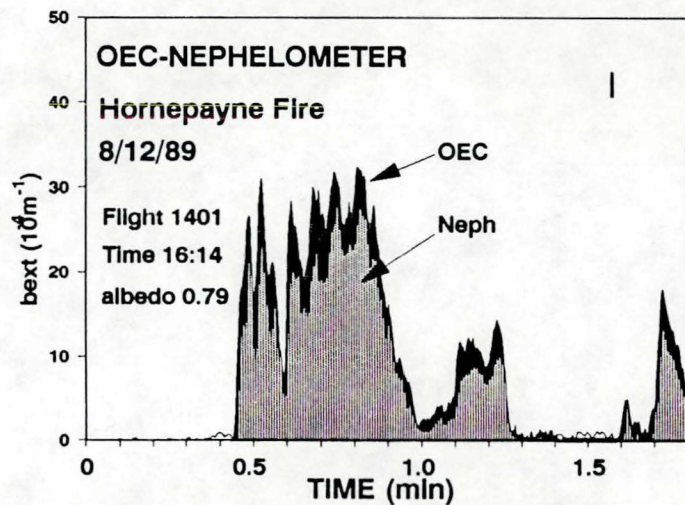
Figure VII E.3



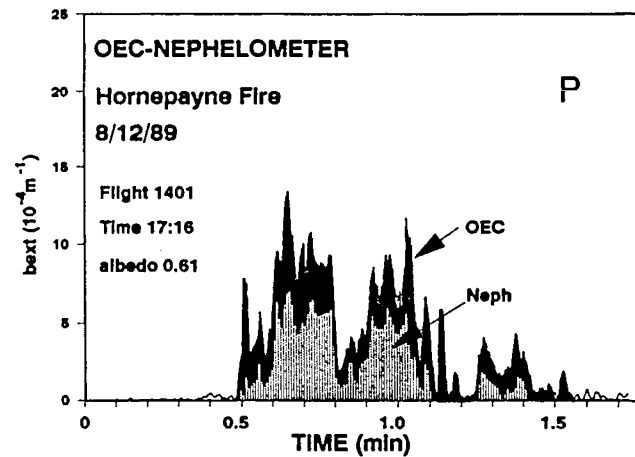
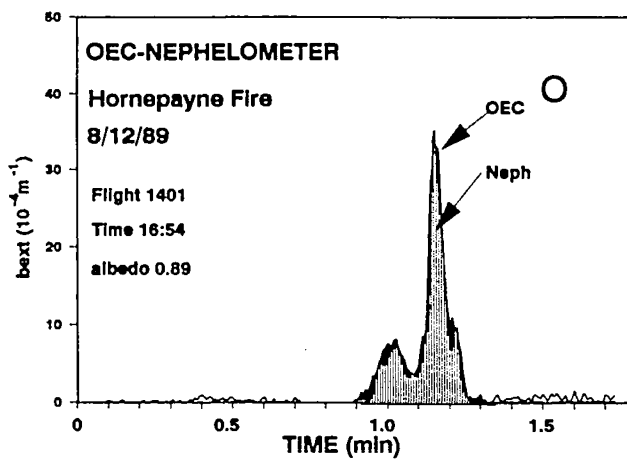
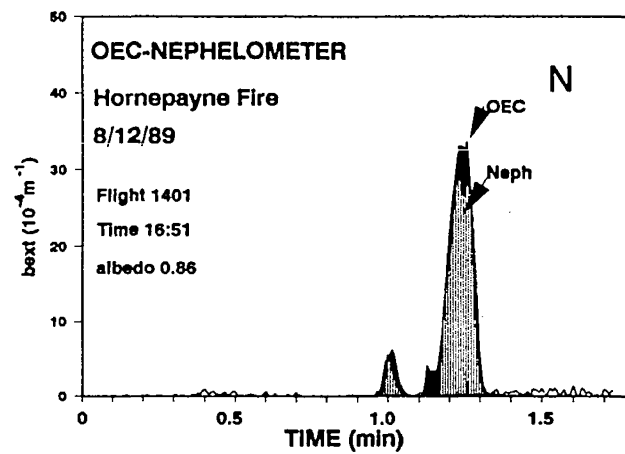
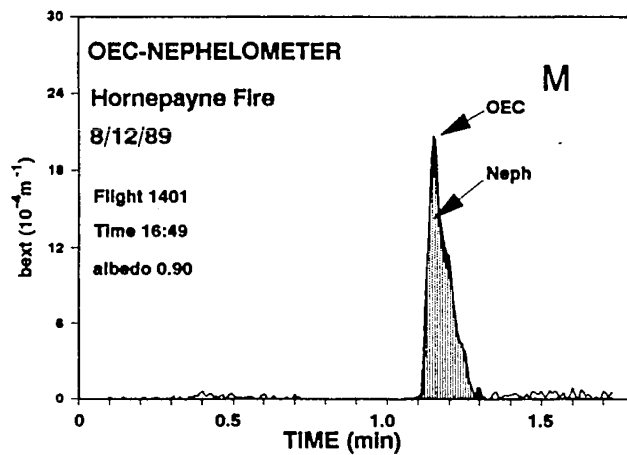
Time Progression of Plume Transects with OEC



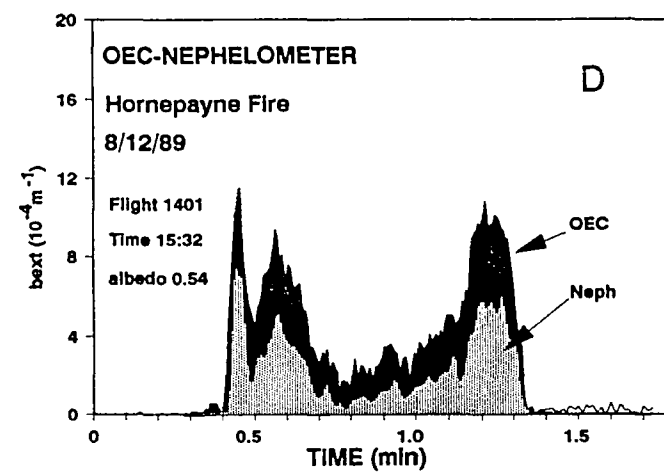
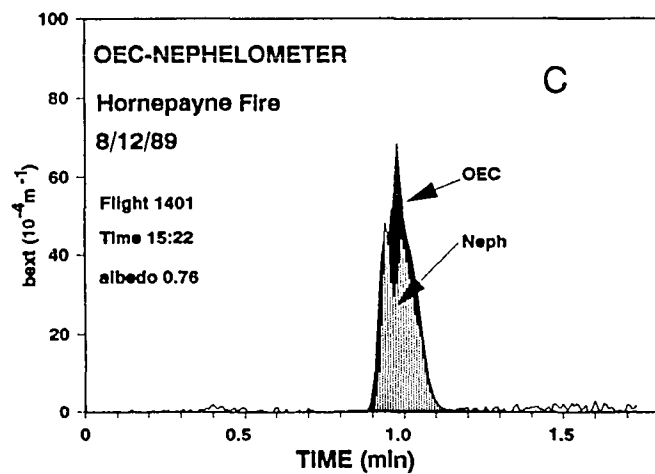
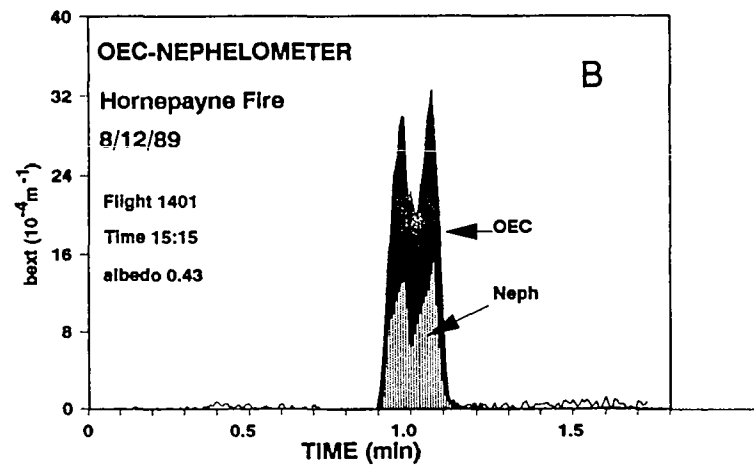
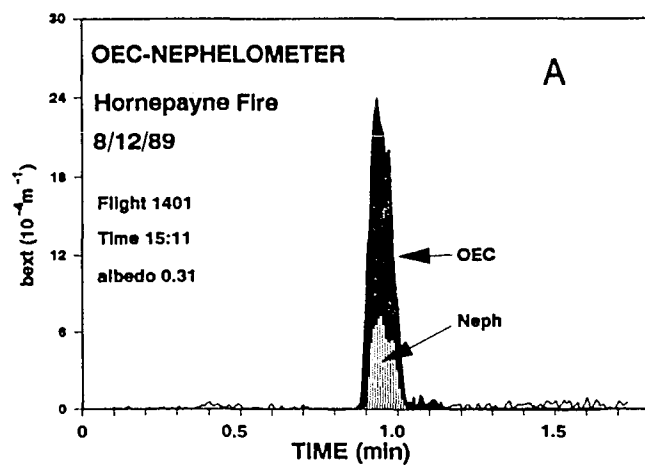
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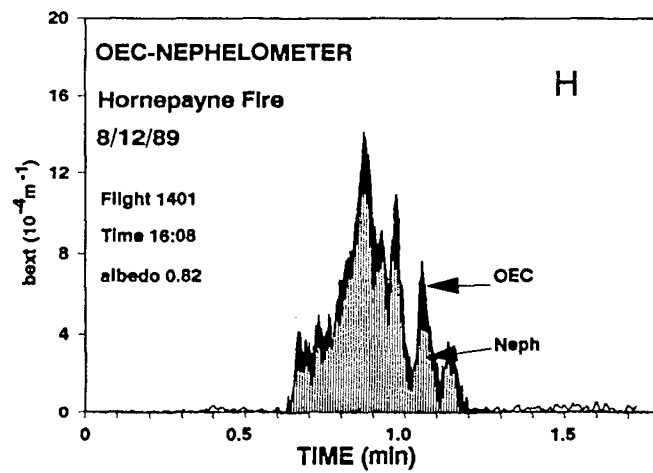
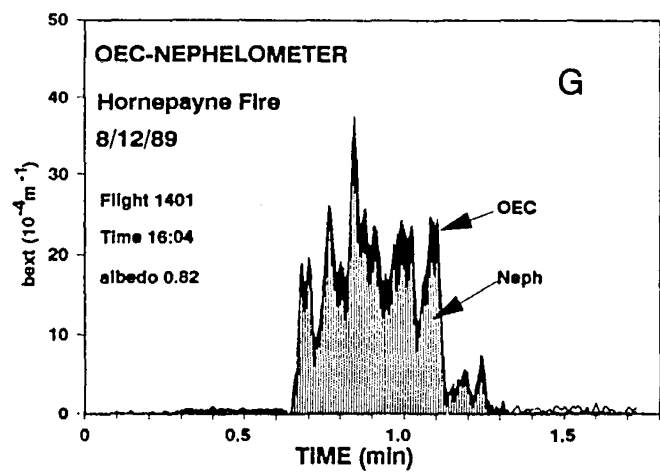
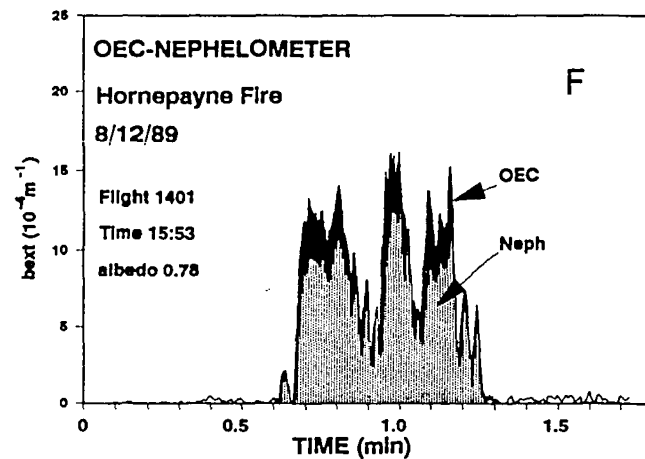
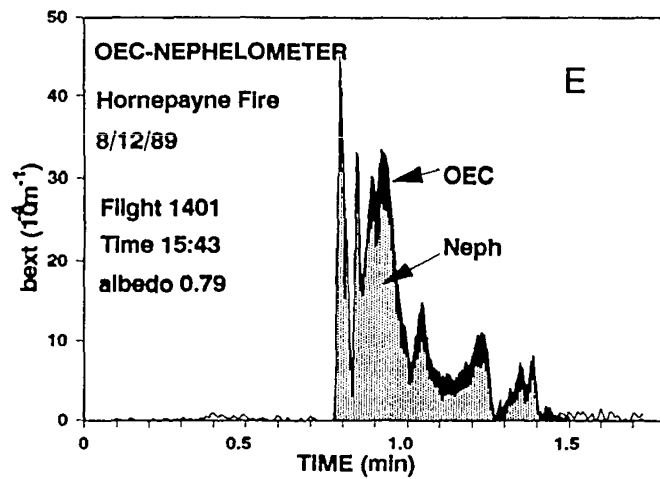
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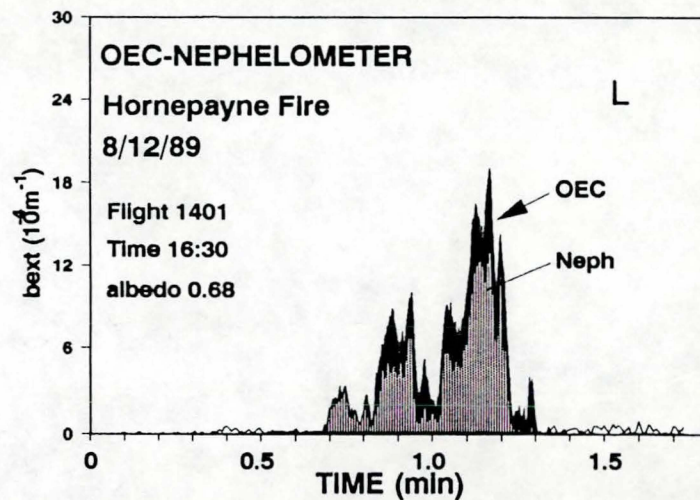
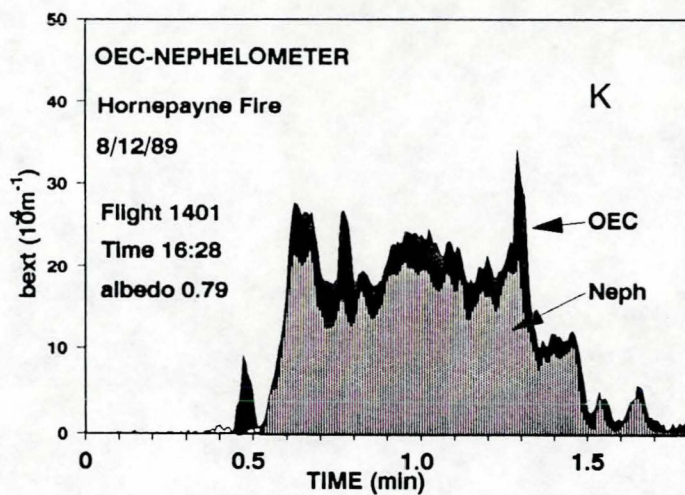
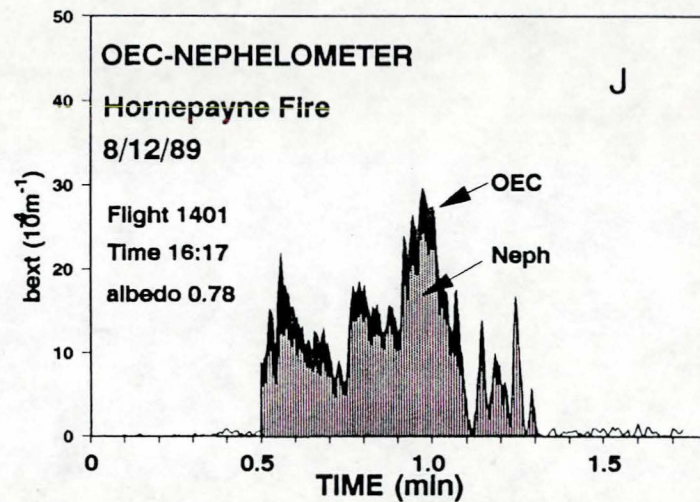
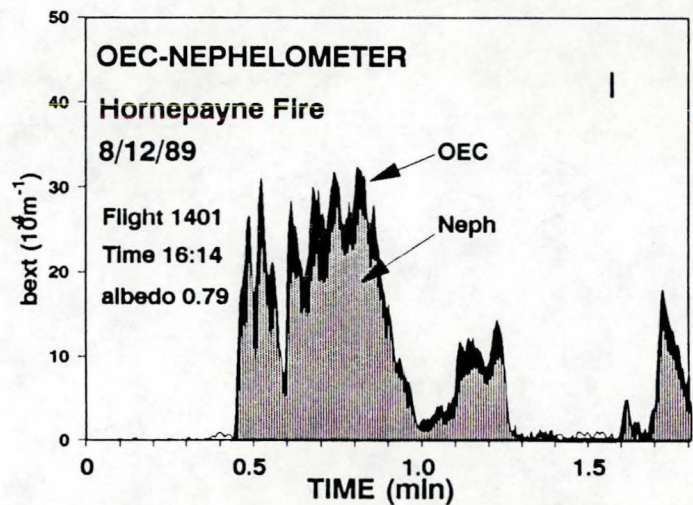
Time Progression of Plume Transects with OEC



Time Progression of Plume Transects with OEC

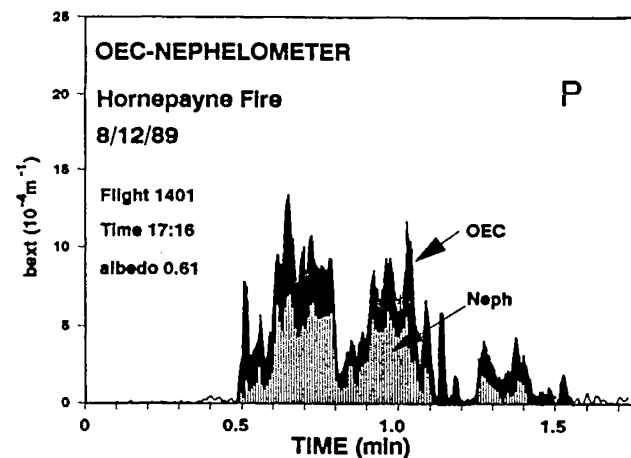
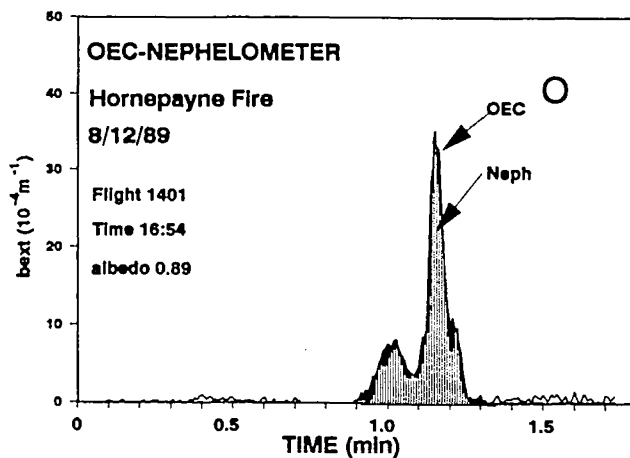
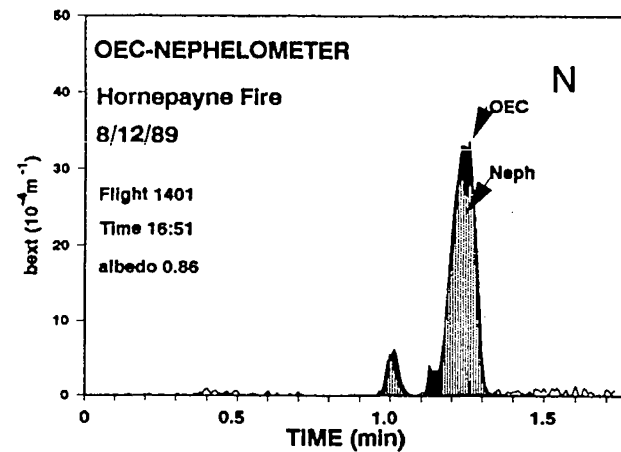
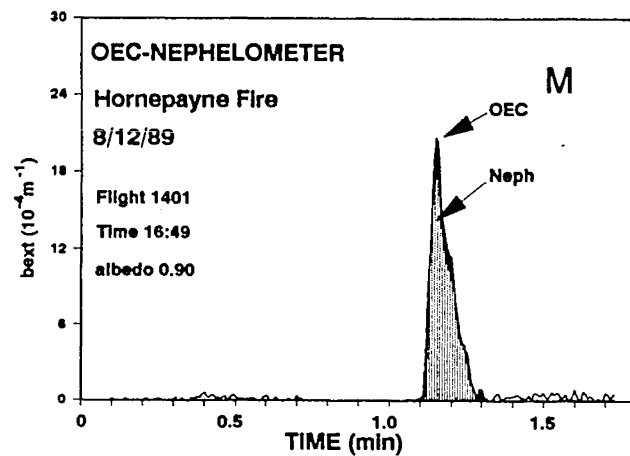


Time Progression of Plume Transects with OEC

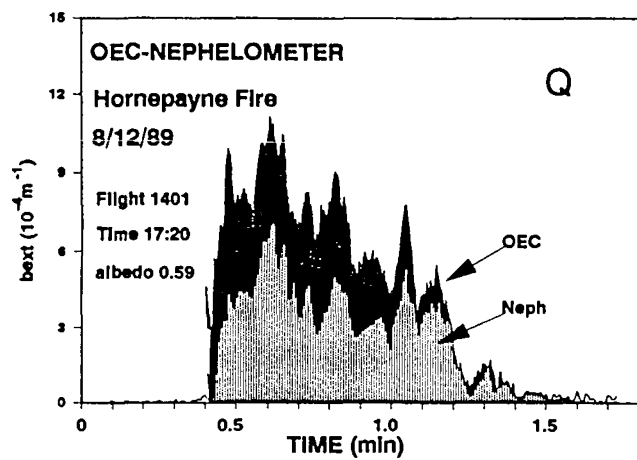


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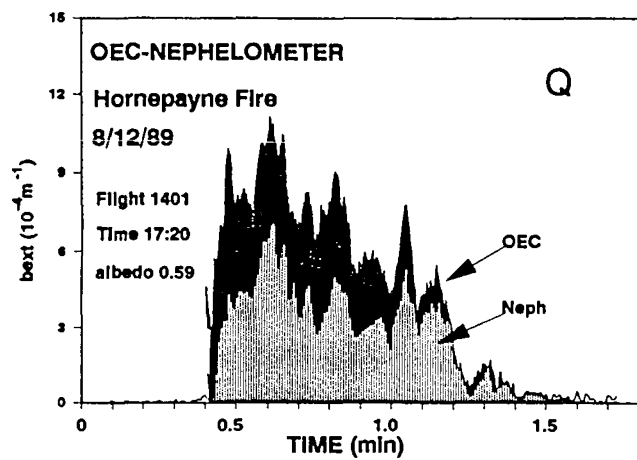
Figure VII E.7



Time Progression of Plume Transects with OEC



Time Progression of Plume Transects with OEC



Time Progression of Plume Transects with OEC

Cloud penetrations were sampled next (M,N,O) and finally, the farthest smoke down wind (P,Q) from the fire was sampled. These last measurements presumably represented the earliest produced smoke (Figs. VII E.5-8).

The albedo measurements in the column represent the darkest smoke observed during the flight with an average albedo of 0.37 (A,B). This suggests an extremely high soot content, perhaps 50 percent, and presumably represents particle production caused by intense flaming combustion at the start of the fire and before any significant dilution by smoldering combustion or gas to particle conversion. The average albedo for detraining smoke was 0.78 which is similar to other fires. The exact mechanisms for increased albedo from detraining smoke is not known, however, gas to particle conversion, coagulation, dilution and scavenging may all be factors. The measurement at 'D' ($\tilde{\omega} = 0.54$) was an attempt at sampling detrained smoke, however, the smoke measured had apparently been carried below the cloud overhang and had not passed through the cloud. The highest albedos were observed in the capping cloud transects with an average of 0.88 for three observations. Liquid water and particle growth are clearly factors affecting these albedo measurements. The last observations were at the farthest locations down wind where significant smoke could be observed. This probably represents some of the earliest (dark) smoke produced. The average albedo for these last two measurements was 0.6 which indicates minimal dilution or conversion during transport of the smoke.

Hill Fire 8/10/89 -

In contrast with the larger burn area at Wicksteed, the Hill fire was only 380 hectares, however, the fire produced extraordinarily high mass concentrations (3-4 mg/m³) in the column and a spectacular capping cumulus. Heavy hail and precipitation were observed and thunderstorm activity was somewhat hazardous, at least to the instrumentation, and limited sampling. Most of the smoke appeared to enter the capping cloud with little detraining. Optical measurements in the early column development were

unsuccessful because extinction caused by the extremely high mass concentration exceeded the capability of the nephelometer ($\sigma_s > 10^{-2} \text{ m}^{-1}$). Only a limited number of optical observations were possible because of high concentrations in the column and the complexity of the weather. It was not always possible to know which smoke features were being observed or how they were related to the multiple ignition phases which characterized this fire. Further work needs to be done here.

The approximate locations of the optical measurements are shown in Figure VII E.9. The letters marking these locations correspond to the smoke optical cross sections shown in Figures VII E.10-11. A description of these figures is given in the previous section describing the Wicksteed fire.

Six optical measurements were obtained: two in the cloud above the column (A,D); two in the detraining smoke associated with rain (or hail) shafts (B,C); one near the edge of the cloud at an altitude of about 3500 m (E); and one in the heaviest observed smoke which had been processed by the cloud (F).

The first two measurements in the developing cumulus, above the column, were transects through narrow bubbles of the cloud. These locations were selected for their promise of finding concentrations low enough to measure. The average albedo for these two observations was 0.85, which is similar to other in-cloud albedo measurements near cloud base. B and C were taken in the detraining smoke below the overhang. C was in a hail and rain downdraft and concentrations were much lower than in B. The albedo was also much higher in C, $\tilde{\omega} = 0.82$ compared with 0.67 for B. This suggests that scavenging may have been important in the hail and rain down drafts. E is somewhat of an anomaly. The transect was through the upper edge of the cloud at about 3500 m. The albedo is extremely low (0.59) for this area of the plume; the first portion of the transect indicates very low scattering relative to total extinction. Since we have only one measurement in this area, no conclusions can be drawn as to the reliability of this observation. The last measurement, F, was through the heaviest detrained smoke,

HILL 8/10/89
Location of Optical Measurements

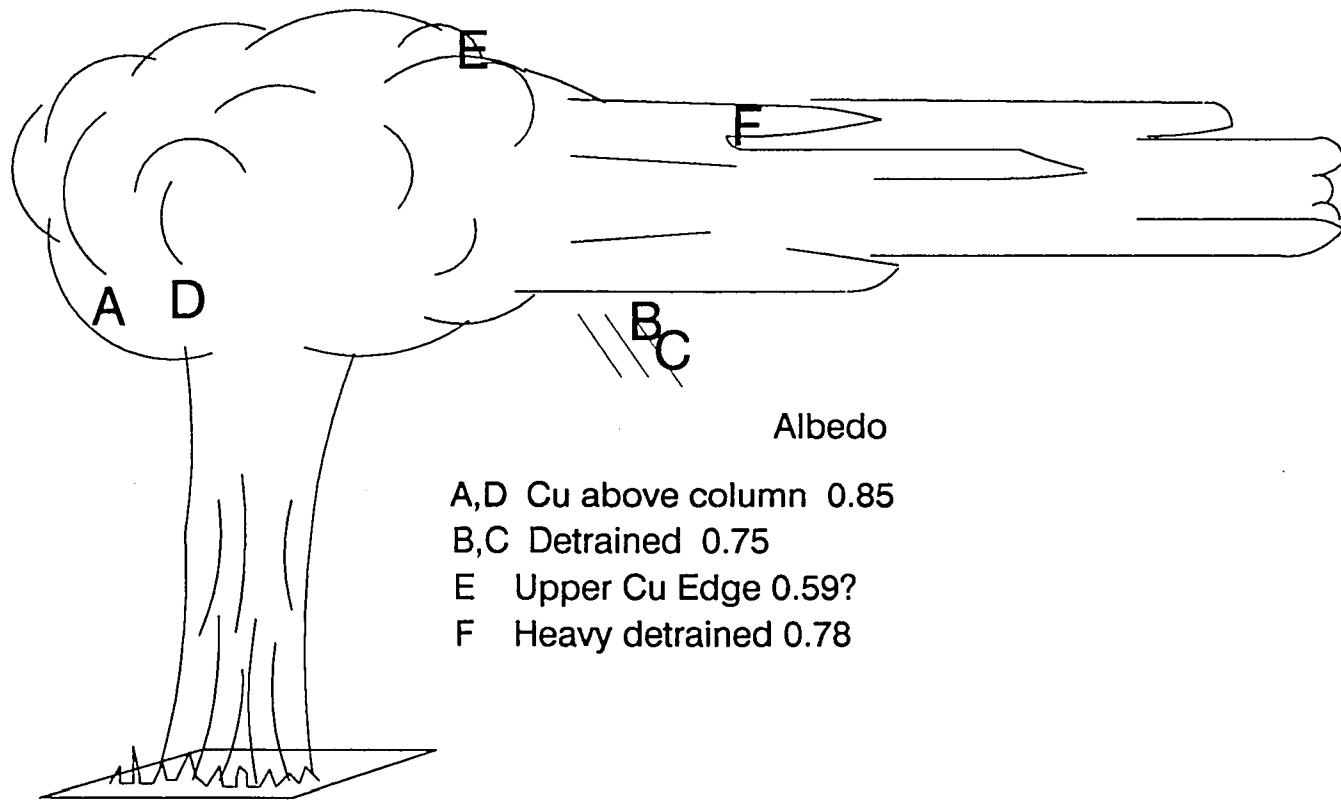
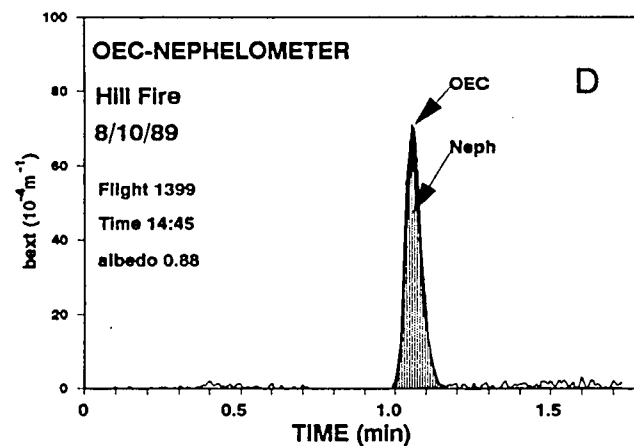
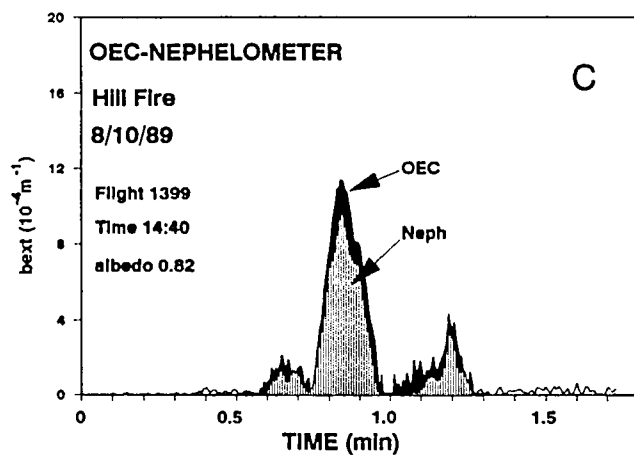
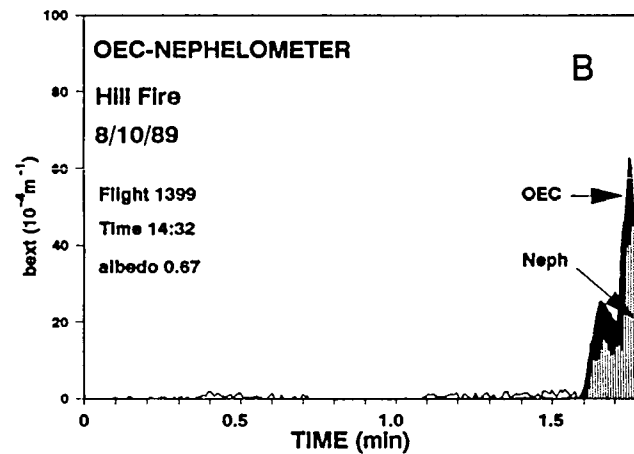
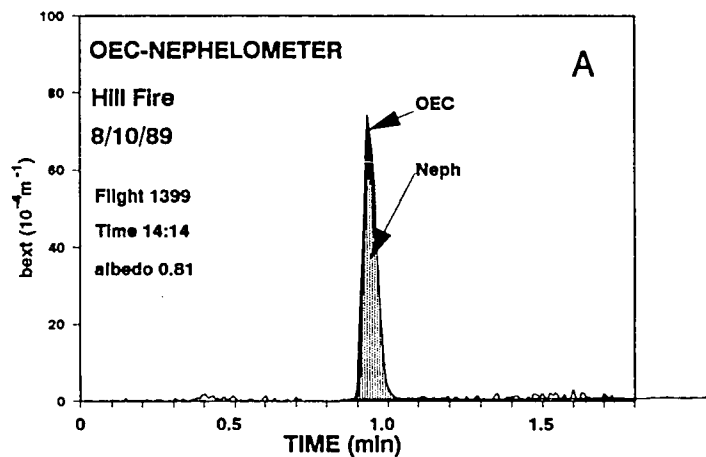
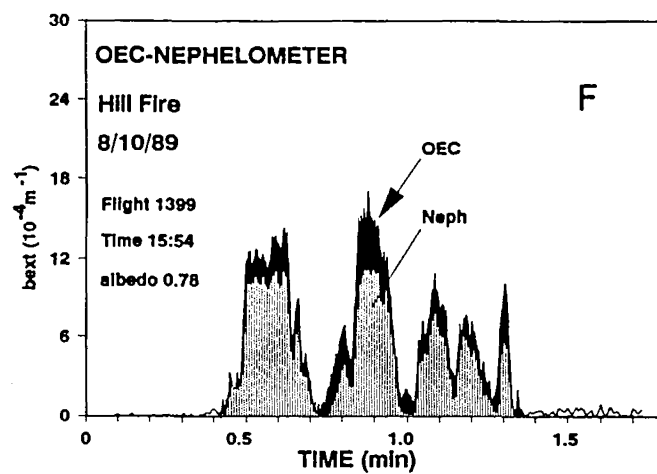
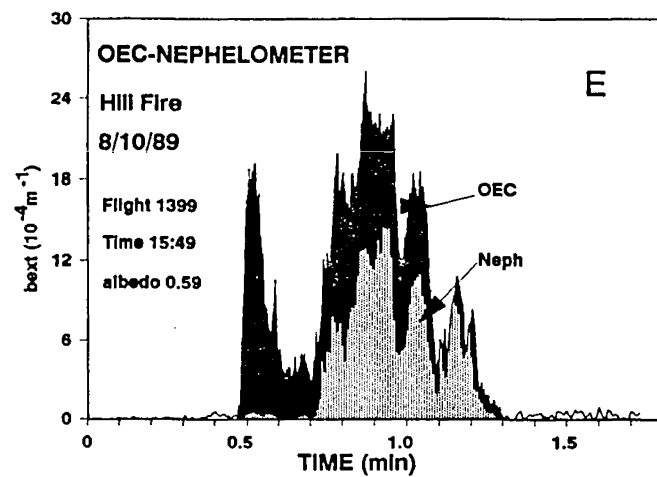


Figure VII E.9



Time Progression of Plume Transects with OEC



Time Progression of Plume Transects with OEC

downwind of the cloud. The average albedo for this pass was 0.78 which is comparable to other observations of detraining smoke after some aging.

Summary

Hill and Wicksteed were very different fires in terms of their complexity. Wicksteed fits a pattern similar to many previous fires in which we have optical measurements. It was well structured with features that were discernable. Wicksteed stands out in the table summarizing measurements from all our previous fires with the lowest average scattering albedo. These averages, however, represented a good deal of smoke not processed by cloud and to some extent depended on the fire stage when the measurements were made. As was seen from the Mabel Lake and Troy fires, measurements of non cloud processed smoke in the early stages of the fire was much darker than in later stages. The Wicksteed measurements were made immediately after ignition and therefore the averages are much lower. Hill was complex because of the extremely high concentrations in the column and the thunderstorm activity. The high concentrations made it impossible to measure the column in the early stages and the cloud activity that developed made it difficult to determine which feature of the fire was being measured. On the average, however, the optical measurements were similar to averages from other fires.

VII. F. CLOUD AND PRECIPITATION SCAVENGING OF SMOKES

Background

In the National Research Council's report, "The Effects on the Atmosphere of a Major Nuclear Exchange" (1985), the Council's top recommendations for fire phenomena research included "the effects of prompt water condensation...and removal rates" and while their intention was not to design a research program, they scored the importance of smoke scavenging..."However, it is worth emphasizing that a particularly important subject that is amenable to both experimental and theoretical study is the microphysical processing (by coagulation and water scavenging) of smoke particles in large fire plumes..." Following this advice we have focused a significant fraction of our effort on experimental measurements of prompt smoke scavenging by fire capping cumulus clouds.

We note that a quick global examination of typical moisture distributions will suggest that in most places and most seasons a fire which is large enough to push smoke into or near the stratosphere (probably a necessary condition for nuclear winter) will probably be capped with a mature thunderstorm, perhaps even a supercell thunderstorm. While the size and intensity range of fires studied has been of necessity on the small end of the phenomena scale, this has been compensated to some extent by having several fires on moderately convectively unstable days. The nature of these convective smoke columns is such that virtually all of the smoke will be processed and scavenged by cloud water and liquid and solid hydrometeors. During this processing the smoke remains a very small part of the smoke/cloud system with condensed water mass typically 10^4 times greater than the smoke mass.

However, before beginning the discussion of how these measurements can be made and the results of our studies we should focus briefly on some relevant literature and the state of our knowledge in this area. Until the 1970's most of the field and laboratory research was carried out on precipitation scavenging (defined as occurring between cloud

base and the surface) and only on the supermicron aerosol fraction. Scavenging by in-cloud processes was largely neglected. Based on reasonable agreement between theory and experiment for supermicron aerosol, the theory for submicron scavenging was rather uncritically accepted. This theory predicted very low removal rates for submicron particles.

Field experiments by Radke et al. (1977) and Graedel and Franey (1977) altered this situation, showing submicron aerosol removal rates $\sim 10^2$ greater than the early theoretical prediction. Our field measurements were expanded by Radke et al. (1980) showing complex dependence of scavenging efficiencies on aerosol and droplet sizes. New theoretical work (Wang et al., 1978 and Leon and Beard, 1978) resulted in an increase in the theoretically predicted scavenging efficiencies for submicron aerosols (up an order of magnitude from earlier work), but a substantial gap still existed between theory and field experiment. In a review of this situation Slinn (1983) concluded that by evoking new mechanisms he could theoretically explain the observed unexpectedly efficient aerosol removal down to sizes of a few tenths of a micron. He agreed with the suggestion by Radke et al. (1980) – a large fraction of these particles could experience deliquescent growth in the humid subcloud environment and thus grow to sizes where inertial removal becomes efficient. Slinn remained unable to explain the apparent comparatively efficient removal below a few tenths of a micron.

We cite this to illustrate a point. Both the experimental and theoretical basis for precipitation scavenging rests on shaky ground with important unresolved differences between theory and experiment. These uncertainties limit both our confidence in our data – are there unknown methodological errors? – and in both use and extrapolation of the available theory. However, both experiment and theory say that the removal of the smoke accumulation mode particles centered at 0.2–0.3 μm diameter by precipitation will be rather slow – very slow if some theories are correct (Flossman and Pruppacher, 1985, 1988)

The removal mechanism likely to dominate the atmospheric removal of accumulation mode aerosol was identified by Junge (1963) as cloud nucleation scavenging.

He suggested removal rates of 50-100% of sulfate aerosol (the dominant component of the background accumulation mode aerosol). Hegg and Hobbs (1983) in a study of scavenging of accumulation mode sulfate and nitrate in small cumulus, stratocumulus and stratus showed removal of typically 60%, but often approaching 100% as a result of a single cloud encounter. Using different methodologies in small cumulus and stratocumulus clouds Radke (1983) showed that cloud nucleation scavenging of 0.2 μm aerosol averaged about 85%. Of course, cloud nucleated particles are not truly scavenged until removed by precipitation, but there is an important intermediate step short of removal to the earth's surface by precipitation. Once a smoke particle is incorporated in a droplet or ice particle, either as the cloud condensation (or ice) nucleus or later by Brownian or phoretic forces, its size for purposes of scavenging increases more than an order of magnitude and inertial collection of smokes, droplets and/or ice particles can proceed rapidly. Also, chain aggregates and other complex aerosol structures may collapse into far more compact forms as the surrounding droplet evaporates. Thus, even if a precipitation particle does not result from these interactions or if the hydrometeor evaporates before reaching the ground, the newly aggregated smoke particle may well be "effectively" scavenged having become large enough for gravitational removal, subsequent inertial removal, or simply have its optical properties changed by particle compaction.

Penner and Molenkamp (1989) review the cloud and precipitation scavenging modeling literature which has developed to theoretically describe the removal processes active in a cumulonimbus cloud capping a large fire. They note the extraordinary range of smoke removal efficiencies predicted (10 – 95%) and its similarity to the uncertainty in the original NRC (1985) estimates of 10 – 90%. Since the NRC's estimates were little more than educated guesses it is clear that we should not look to theory for guidance. Penner and Molenkamp concur..."None of the calculations have considered the range of scavenging pathways necessary for prediction of removal..." In view of the inadequate

treatment of these issues, a range in the amount of smoke scavenged by precipitation above nuclear fires of from 10 – 90% (NRC, 1985) is still valid.

Experimental Opportunities and Methods

In the present sequence of experiments we have examined 17 biomass fires or fire complexes. Of the 17 experimental periods 10 featured fire capping cumulus clouds and four reached cumulonimbus proportions. Of these four, "Hardiman" produced only light to modest precipitation and none may have reached the ground. At the other end of the intensity scale "Hill" developed into a persistent, mature thunderstorm with heavy precipitation. Of the five large prescribed fires studied (> 100 ha) only one failed to produce a large capping cumulus. Three of our fires were multiple lightning ignited wild fires in the mountainous terrain of Idaho, Oregon and California. While these wild fires burned over huge areas (the Silver fire burned nearly 30 days) the fires were more properly described as many small fires over a large area and in general only modest cumulus developed during our observations.

All of these fires were targeted as possible scavenging experiments and all except "Abee" produced some results which we considered valid. Abee produced indications of significant scavenging which now appears to be a combination of scavenging and change of fire behavior which is unlikely to be deconvoluted.

Our approach to measuring scavenging efficiencies depends on a variety of sampling schemes all of which face some difficulties for a single aircraft experiment. The choice of which approach to try depends on circumstances largely dependent on fire scale. The schemes which we have used are listed below along with a brief critique:

1) Input-Output: This is potentially the simplest and most powerful approach which requires you to measure an aerosol property (mass size, distribution, etc.) along with a conservative tracer believed to be proportional to the aerosol emitted (e.g. CO ?) in the

ascending smoke column and exiting the capping cumulus cloud. The conservative tracer allows correction for dilution by the smoke mixing with ambient air inside of the cloud.

*The method requires a period of steady state emission.

2) Emission Factor: We initially believed (based on ground observations) that the evolution of the particulate emission factor would be relatively slow as the phase of the fire moved from flaming to smoldering. Thus a combination of emission factors measured at below cloud base, in-cloud but sampled interstitially (between cloud particles) and exiting the cloud, would provide a useful measure of scavenging.

*Again it requires a steady-state fire (something that we generally do not observe), however, unlike 1) dilution correction is not required.

3) Interstitial: Measure the ratio of the smoke (or a surrogate for smoke) interstitial to the cloud droplets and in the cloud droplets. After converting the amount in the cloud droplets to an equivalent air concentration (see Hegg et al., 1984) the ratio produces directly the scavenging fraction for the accumulation mode aerosol.

*If a surrogate for smoke is used (we used the sulfate accumulation mode aerosol co-emitted integrally with the smoke) one must be satisfied that smoke is scavenged similarly (we are).

4) Cloud Water: Measure in close time proximity the smoke concentration going into the cloud and the amount of smoke in the cloud water. Using volumetric and cloud liquid water content measurements to yield equivalent air concentrations, the amount of accumulation mode aerosol scavenged is determined.

* The problems with 3) apply, in addition errors will be introduced if precipitation has begun.

Our initial efforts focused on 1) Input-Output and 2) Emission Factor methods and of these, only our work with 1) remains active. Method 2) simply does not provide consistent results. Method 1) is most valid using small cumulus since if the initial measurement is made just below cloud base and then immediately you climb and measure

the smoke escaping the cloud, the period of required steady smoke emissions can be very short.

Of the small cumulus cases examined, especially the several cumulus capped wild fires (Myrtle/Fall Creek) and the Troy planned burn, no significant scavenging occurred in the accumulation mode smokes. Significant removal of the supermicron aerosol was observed.

Hardiman was the first fire producing clear results by method 1). The aerosol property examined was the size distribution. Figure VII F.1 shows the input and output smoke size distributions developed by this method. The log-log presentation somewhat masks the extent of the scavenging shown more clearly in Figure VII F.2 as smoke percent removed. Here we see most of the supermicron aerosol removed ($\sim 80\%$), a removal minimum at $\sim 0.3 \mu\text{m}$ in diameter and then increased removal up to nearly 40% in the center of the accumulation mode mass peak. This is quite significant removal for a cumulus of modest depth and only the slightest precipitation.

The following year Battersby provided a similar opportunity to use Method 1) and Figure VII F.3 again shows the percentage of the smoke removed. Battersby with deeper convection and more precipitation shows some similarities to Hardiman's scavenging with removal in one case approaching 100% of the supermicron aerosol. Again, a removal efficiency minimum appears at $\sim 0.35 \mu\text{m}$ with one sample showing similar accumulation mode removal ($\sim 40\%$) and the second sample a remarkable 90%. We emphasize that these results are for scavenging by all mechanisms.

Measurements of the droplet size distributions just above cloud base (see Fig. VII F.4 for an example from the Battersby cumulus) allows us to evaluate the role of cloud nucleation scavenging. This process is outlined in Table VII F.I. Basically if the peak in the droplet size distribution (number) is taken to be the "embryo" droplet size which has condensed on one smoke particle, then dividing the volume of the embryos into the total droplet volume gets you approximately back to the total number of smoke particles

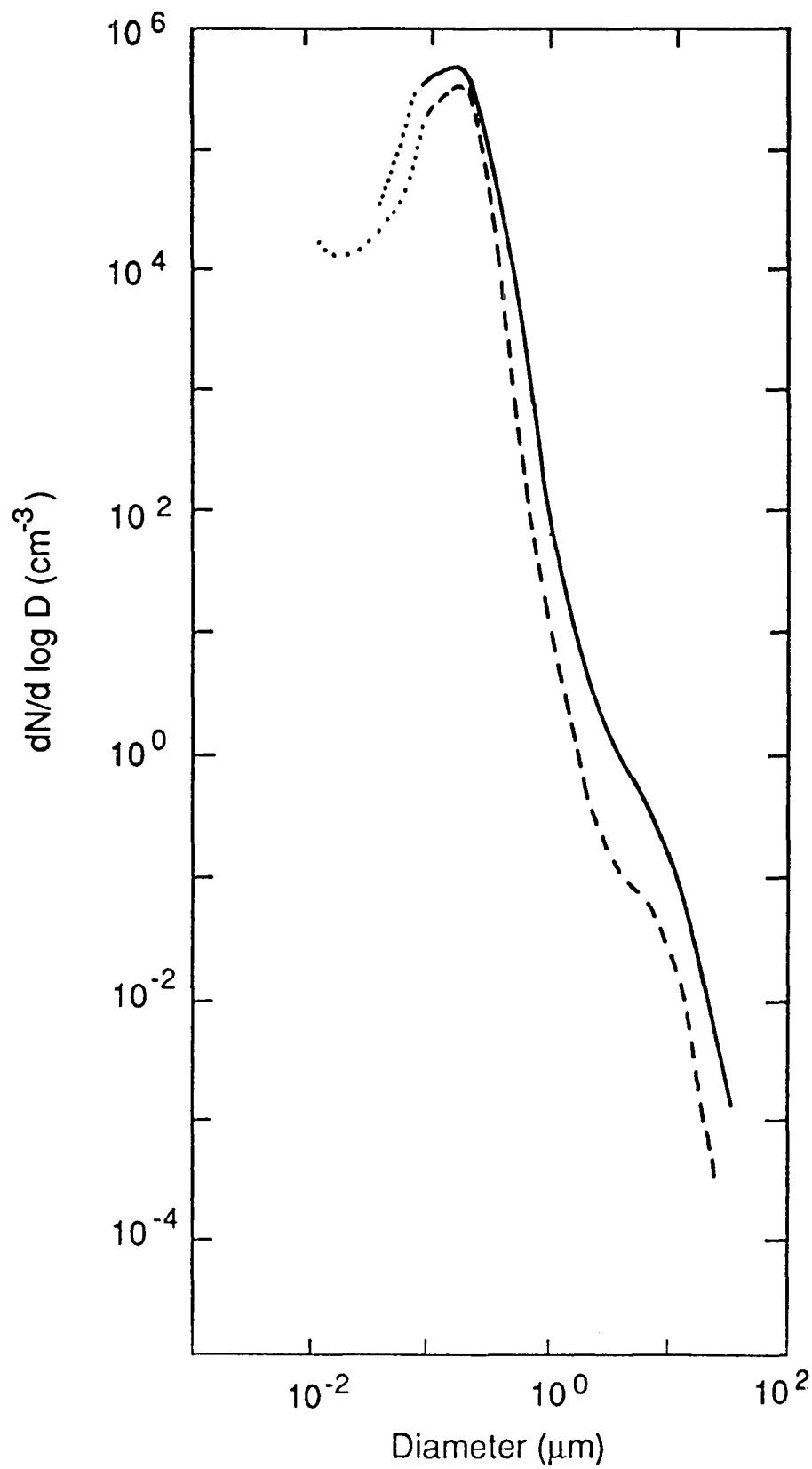


Figure VII F.1 Smoke particle size distributions altered by cloud and precipitation scavenging over the Hardiman biomass fire.

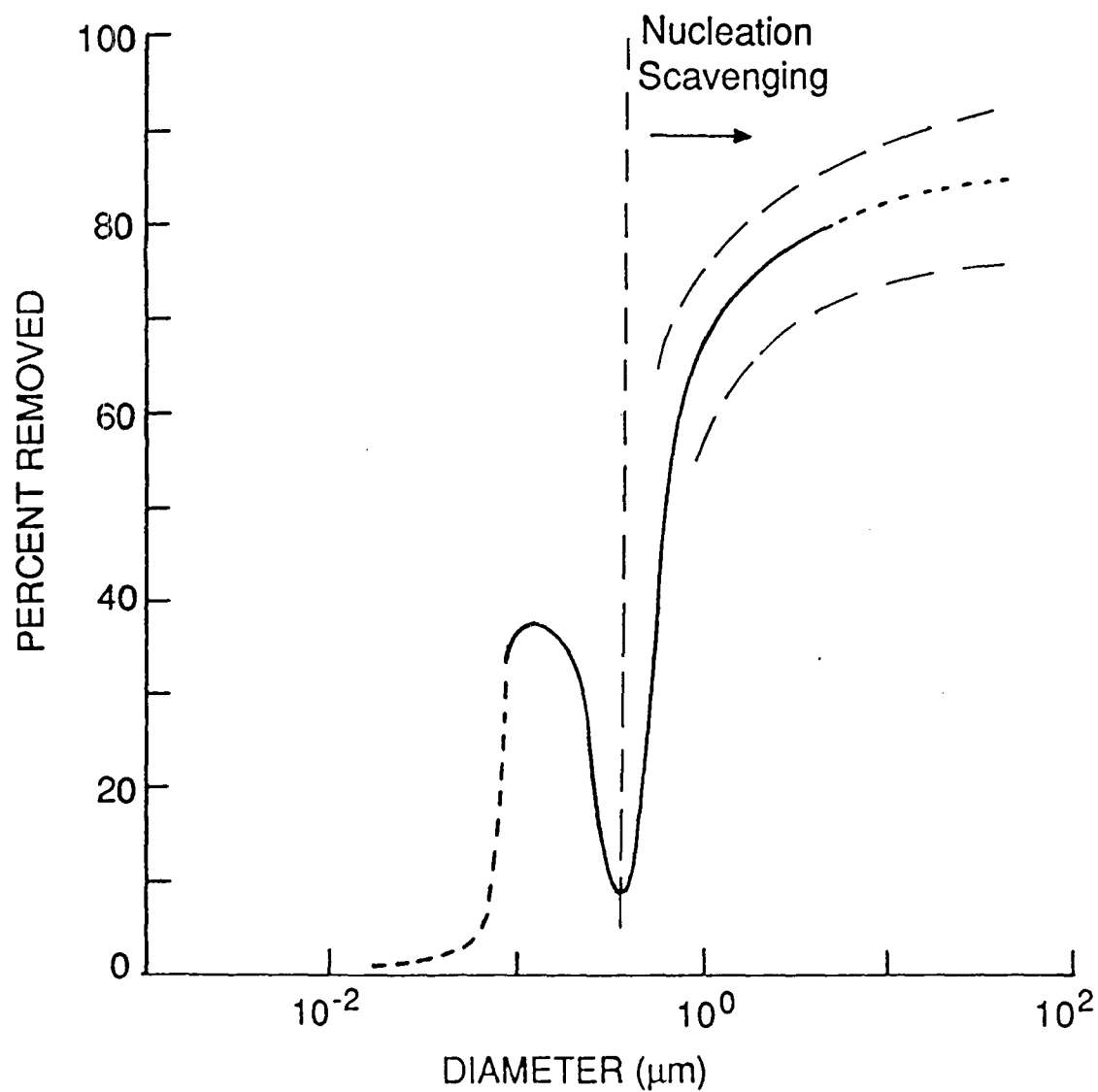


Figure VII F.2 Percentage of the smoke removed by cloud and precipitation scavenging as a function of smoke particle size over the Hardiman biomass fire. The vertical line marks the calculated tower size limit of a nucleation scavenging mechanism

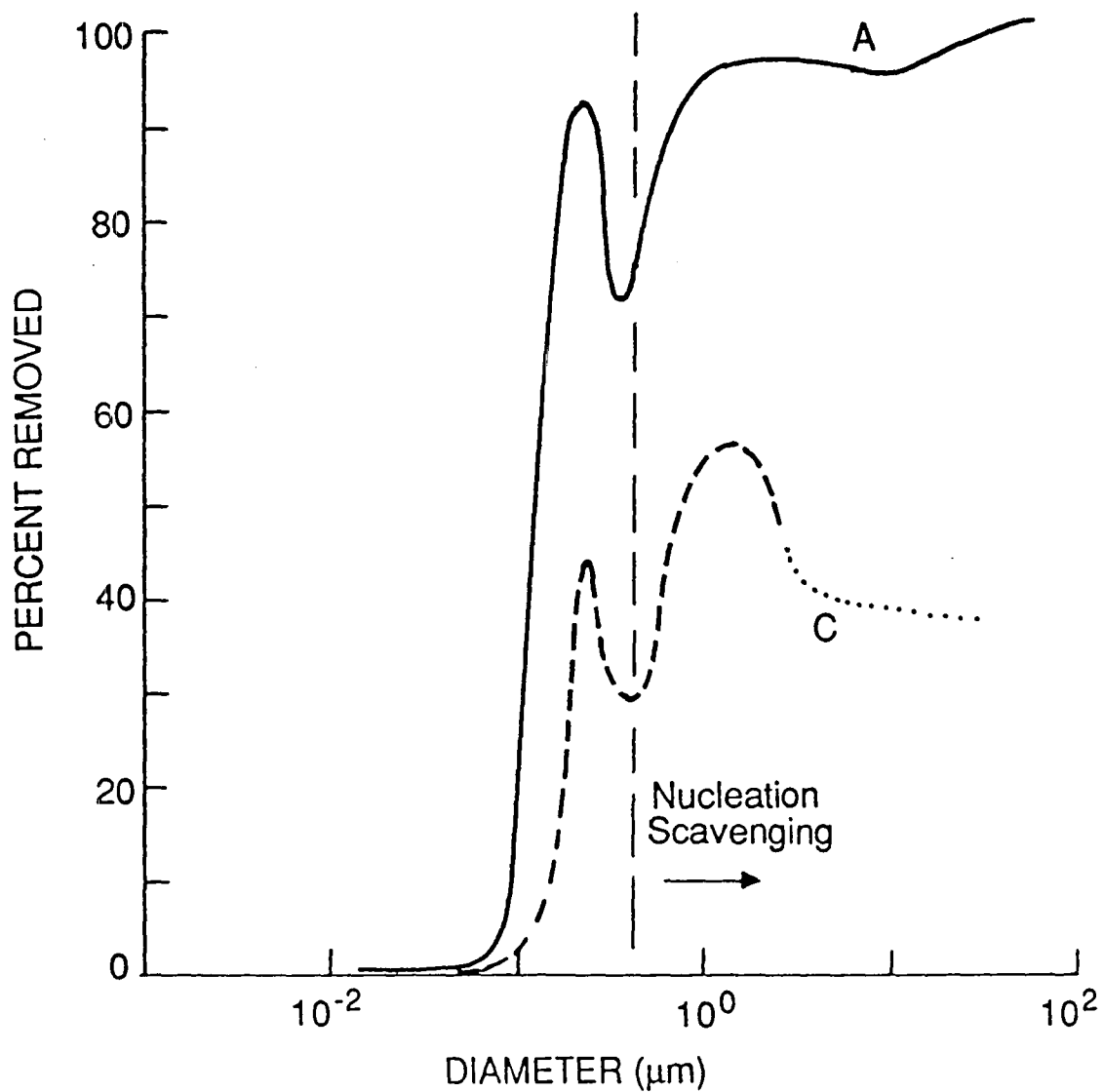


Figure VII F.3 Percentage of the smoke removed by cloud and precipitation scavenging as a function of smoke particle size over the Battersby biomass fire. The vertical line marks the calculated lower size limit of a nucleation scavenging mechanism.

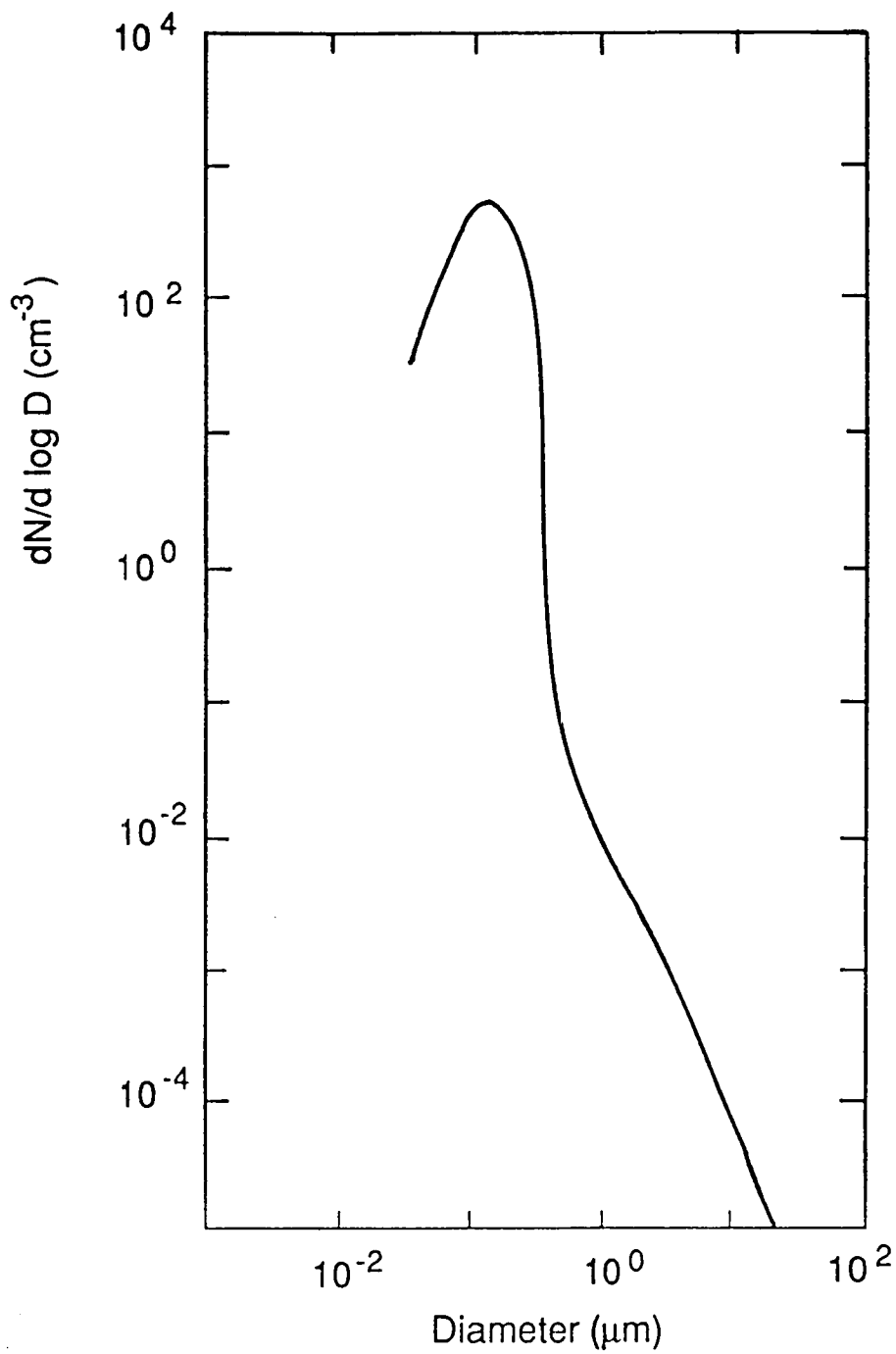


Figure VII F.4 Characteristic droplet size distribution in lower third of Battersby capping cumulus cloud.

Table VII F.I PRELIMINARY ESTIMATION OF
NUCLEATION SCAVENGING

Simplifying Assumptions:

- 1. The droplet size of the peak number concentration is equal to the 'embryo' size
- 2. There is one nucleating particle per 'embryo'
- 3. All nucleating particles are smoke particles

	HARDIMAN	BATTERSBY
Diameter Peak Droplet Concentration (μm)	4.8	12.5
Equivalent 'Embryo' Volume (μm ³)	57.9	1022.6
Total Droplet Volume Concentration (μm ³ cm ⁻³)	1.75 x 10 ⁵	5.06 x 10 ⁵
Number 'Embryos'	3022	495
Total Aerosol Number Concentration (cm ⁻³)	2.16 x 10 ⁵	4.20 x 10 ⁵
Minimum Aerosol Diameter Removed by Nucleating Droplets (μm)	0.32	0.40

nucleated. Such a procedure, of course, ignores vapor condensation, but this is partially corrected for by choosing the mode peak droplet size rather than the minimum size. Regardless, the result is very interesting as it predicts removal by nucleation scavenging down to 0.32 μm for Hardiman and 0.40 μm diameter for Battersby. This removal size precisely marks the minimum in scavenging efficiency shown in Figures VII F.2 and VII F.3. The mechanism which is responsible for the efficient removal from 0.1 to $\sim 0.3 \mu\text{m}$ shown as the second removal mode in these figures is uncertain. However, it is clear that significant smoke scavenging occurs with the onset of only slight precipitation and appears to grow with precipitation intensity.

The Hill and Wicksteed cumulus complexes were much larger than Hardiman with tops about 7-8 km and roughly comparable to Battersby. Data for repeating these scavenging calculations with the Hill and Wicksteed fires exist, but because of concern with the stability of the calibration of one of the aerosol instruments we have deferred these calculations and we have concentrated on scavenging estimates from Methods 3 and 4 which are summarized in Table VII F.II.

The Hill experiment provided good data for a calculation by Method 4 yielding accumulation mode scavenging efficiencies of 40-50%. The same method applied at Wicksteed showed $\sim 80\%$ removal. However, at Wicksteed we obtained data for Method 3 as well which resulted in virtually identical results, 75% of the accumulation mode aerosol is scavenged. This is clearly a milestone in our scavenging work obtaining identical results by two different techniques.

It is tempting to speculate that the difference between Hill and Wicksteed scavenging into cloud water are related to the cloud's input smoke flux. The smoke flux at the times of the samples is roughly three times greater for Hill's cumulus cloud. If the accumulation mode smoke were being mostly nucleation scavenged, the theoretical studies of Jensen and Charlson (1984) suggest that some limits could be reached that are inversely proportional to the input concentration. This would be in accord with our observations.

Table VII F.II Submicron aerosol mass scavenging efficiencies using cloud base aerosol, cloud water, and cloud interstitial aerosol samples

Fire Hill	Method 3 "Interstitial"	Method 4 "Cloud Water"
		50 ± 30%
		40 ± 20%
Hornepayne	75 ± 20%	80 ± 50%

However, since it is not clear that nucleation scavenging is the primary route by which the accumulation mode smoke enters the liquid water phase (in fact, Battersby data suggests it is not) our speculation is probably premature.

Regardless, the four large Canadian planned burns which produced cumulus complexes have provided us with significant new experimental evidence indicating that scavenging of biomass smokes "promptly" by capping cumulus clouds can be quite efficient. This is not to say that the techniques and data are free from flaws. We frankly recognize that our approach is crude and our data set quite limited (additional valid data may yet be extracted from the 1989 data set). Nevertheless, the picture which emerges from this work is:

- Supermicron smoke aerosol is removed with considerable efficiency in all but the smallest capping cumulus clouds. It is almost certain that these particles participate in early production of precipitation sized particles.
- Accumulation mode smoke aerosol (the bulk of the smoke with potentially great atmospheric residence times) enters the cloud water with great efficiency (40-80%) and is removed from the system with equal efficiency (30-90%) by precipitating cumulus with depths greater than 2 km.

VII.G AIRBORNE LIDAR AND INFRARED IMAGING

INFRARED IMAGING

Introduction

A Texas Instruments AAQ-17 FLIR (operating in the 10-14 μm wavelength region) was deployed aboard the C-131A for both the Hill and Wicksteed fires. The instrument was mounted on the after-belly section of the fuselage where it had an excellent field of view. While we considered this year's effort to be both preliminary and exploratory, we intended to confront the FLIR with a variety of optically challenging environments associated with the large fires.

Specifically our tasks were: 1) To use the high resolution and large dynamic range of this FLIR to see if it is possible to improve on previous efforts to map actively burning areas and to measure fire heat flux. Previous efforts have been limited by dynamic range limitations; 2) To use the FLIR's high resolution to observe, in detail, complex fire behavior normally obscured by smoke; 3) If the smokes obscure the FLIR, to use in situ measurements and a combination of geometry and forward and downward video cameras to measure IR optical extinction coefficients.

We achieved limited success in all three tasks, however, as will be described, our successes were more in the nature of gaining guidance on improved measurement techniques.

Image Processing

The FLIR video was recorded on a Sony Professional VO-5800H cartridge video recorder. The VO-5800H/AAQ-17 system produces images of very high resolution in Radio Standards (RS) 343A format. Unfortunately, the RS 343A format is unpopular and seldom used, and the CORECO 0C-300 Image Processor and Frame Grabber has proven unable to "grab" video frames correctly. As a result we have been forced to apply an electro-optical conversion to RS-170 with resultant loss in resolution (875 lines per frame

to less than 430 lines per frame). At this resolution the image processor was able to generate grey scale, false color and (from other video sources) true color overlays and create a tagged information file (TIFF) suitable for further manipulation using PC technology (we have used PC-Paintbrush 4.0+).

Fire Area

For purposes of observing the fire spread rate, especially during the early portions of the fire, the FLIR worked very well as illustrated in Figure VII G.1. In this figure we view the Wicksteed fire at a slightly oblique angle at 1507 LDT. The helitorch is spreading fire in an opening spiral. The image is in false color with red representing the highest temperatures. The progression then moves through orange, yellow, green, and blue before reaching black which represents the lowest temperatures. The helicopter and the suspended helitorch are both visible and marked on the figure. The only clearly resolved ground feature is the roadway which slants from the upper left to the mid-right of the frame. The pilot is igniting biomass on both sides of the roadway. The smoke, which appears very dark and heavy at visible wavelengths, is easily defeated during this phase. However, as the early flaming phase continued into more smoldering activity we attempted to resolve gradations in surface radiance noting that the flaming areas had saturated the FLIR sensor. The dynamic range was adequate for this use, but when we did so we also lost essentially all of the background detail blinding the FLIR except to look for very hot spots.

Thus the dynamic range of the FLIR was of little scientific utility without constant gain and constant adjustment. Since these values could not be recorded precisely, we compromised taking most of the data so that surface detail could be observed thus allowing the FLIR sensor to saturate.

Figure VII G.2 is a similar oblique false color image taken at ~600m above ground with the narrow field of view across the entire Hill fire area at 2011 LDT. This is very late in the event and the fire area has only isolated flaming areas, but still a great deal of

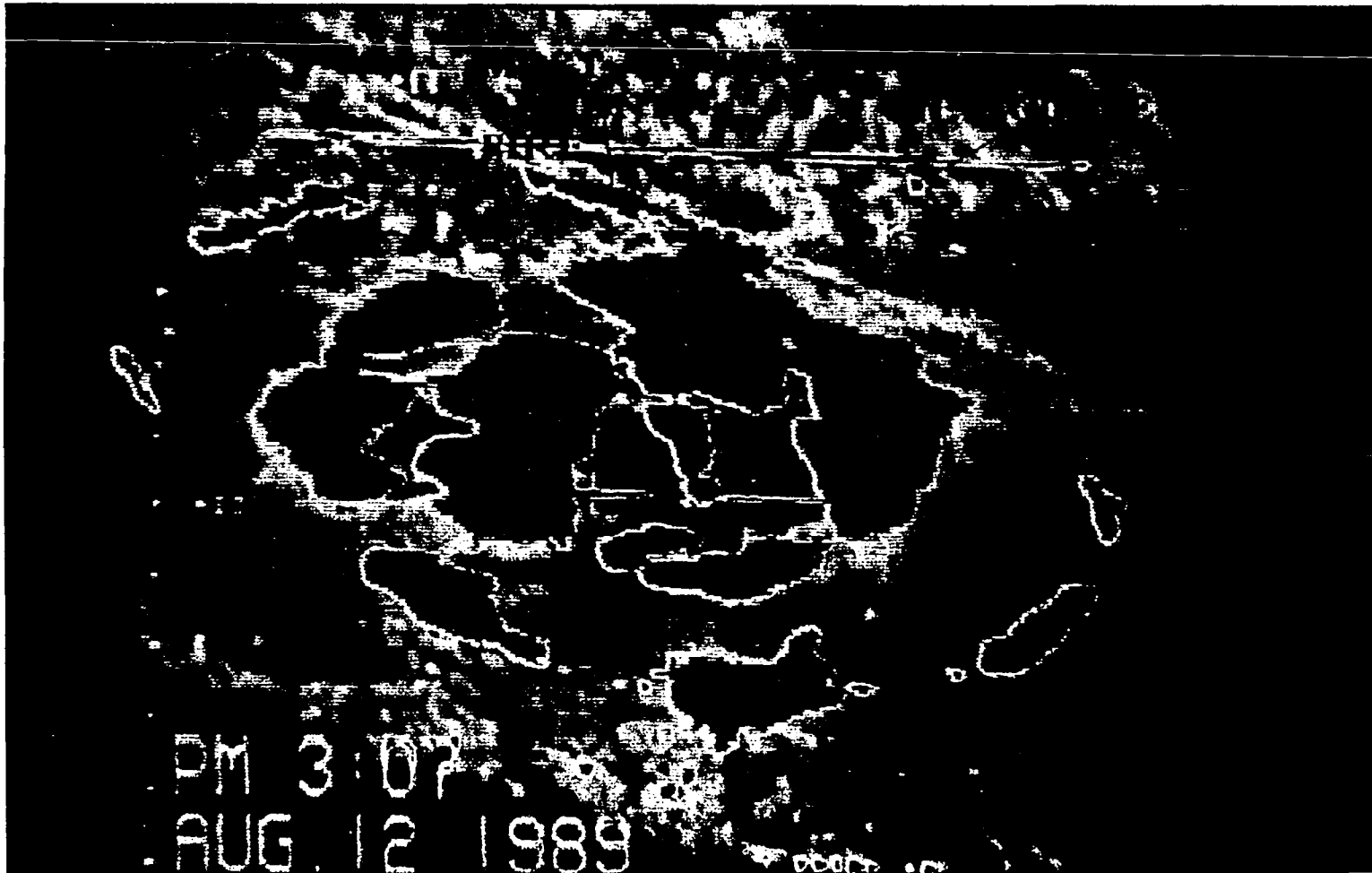


Figure VII G.1 False color infrared image of the Wicksteed fire at 1507 LDT. See text for description of color scale.

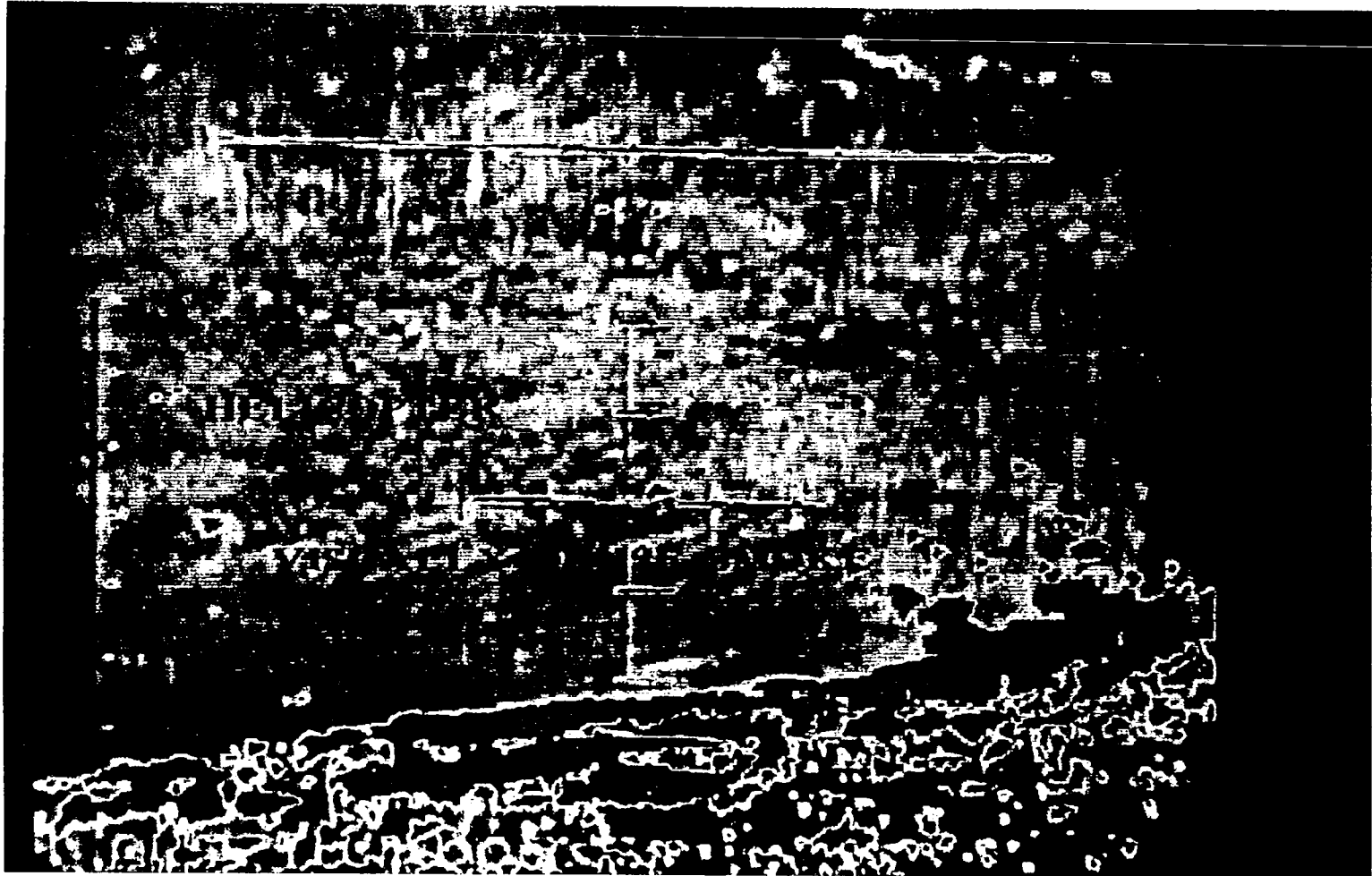


Figure VII G.2 False color infrared image of the Hill fire at 2011 LDT. See text for description of color scale.

smoldering biomass producing a visually impenetrable pall of smoke. The FLIR is easily able to see across the fire and pick up one of the project's helicopters at the cross-hairs in the image. In this copy only the exhaust gas, heated surfaces and engine area are visible. In the background the vertical features are tree trunks. Later, moving away from the fire, Figure VII G.3 shows most of the fire area now at wide field of view. The forest land above the fire area now appears as soft light blue "fluff" with one of the lakes in the area in the upper portion. The speckled red spots in the foreground are the isolated hot spots remaining in the earliest ignited area. Here false color was very useful in analyzing the image. Again the heat and smoke from the now dying fire is not perceptibly obscuring or distorting the image. Figure VII G.4 is a vertical image at 1755 LDT with only a modest reduction in gain compared to the three earlier images. A "cool blue" roadway is seen stretched across the area of the fire. In this image we have a few isolated very hot (flaming still?) spots (red); much larger smoldering areas (orange) and much hotter than background blue/white areas resolved. Note how rapidly some of the areas cooled to near background temperatures.

Fire Phenomena and Obscuration

While the FLIR was generally able to see clearly through a great deal of smoke, the periods of very high heat release often lofted sufficient ash and debris to degrade our image. This also allowed us to image an excellent example of a tornadic fire whirl (Fig. VII G.5). The image orientation is near vertical with the foot of the whirl at the edge of the image near an intense area of the fire (blue/white). The whirl expands as it climbs toward the aircraft and then dissipates in a "smoky" area further from the foot of the image. In this figure, we are clearly imaging smoke in the far infrared. This is puzzling at first glance since super micron smoke and debris should obscure and degrade the image. Why, in this grey (blue) scale, should they (the super-micron particles of smoke and debris) be white

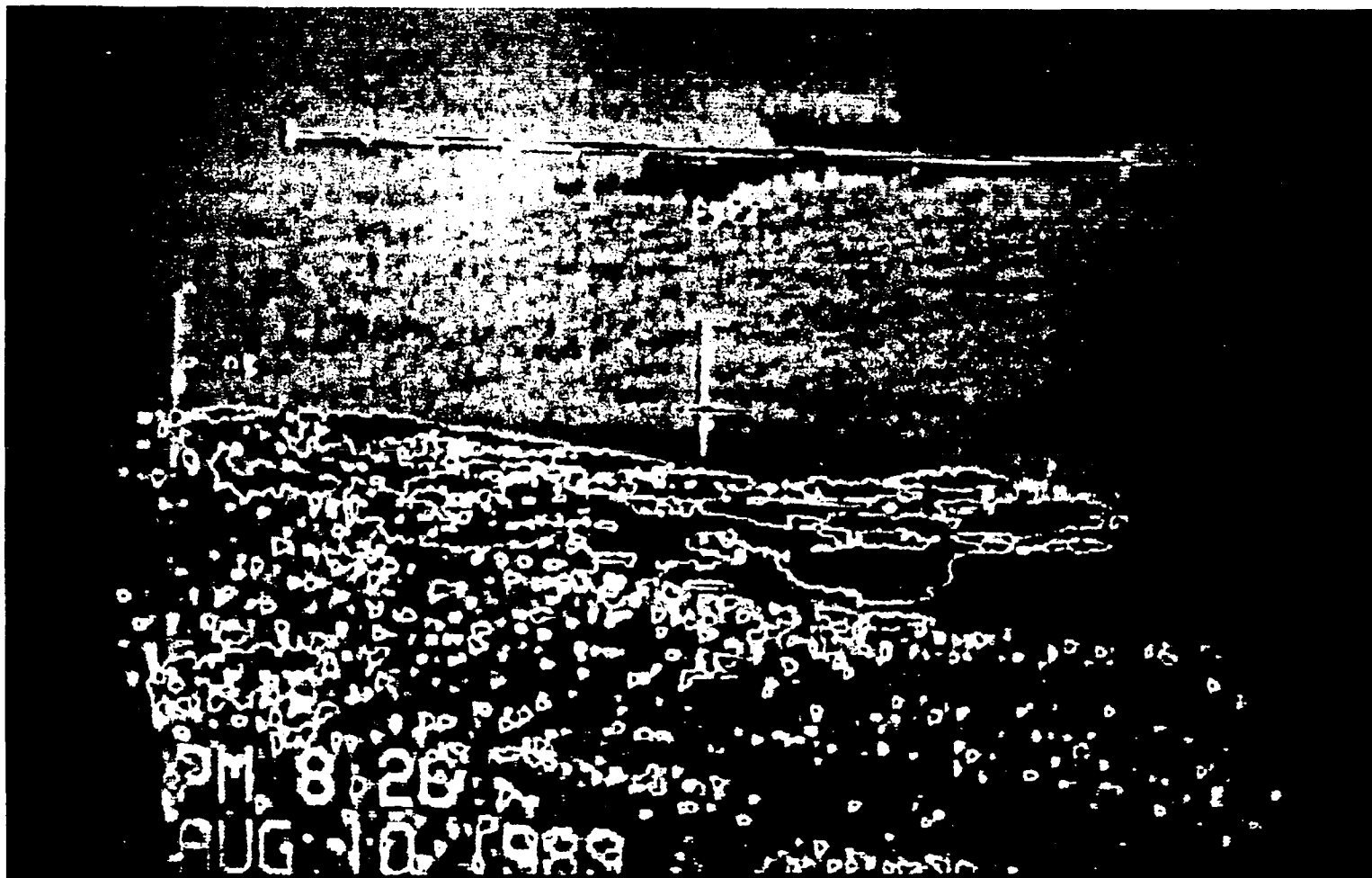


Figure VII G.3 False color infrared image of the Hill fire at 2026 LDT. See text for description of color scale.

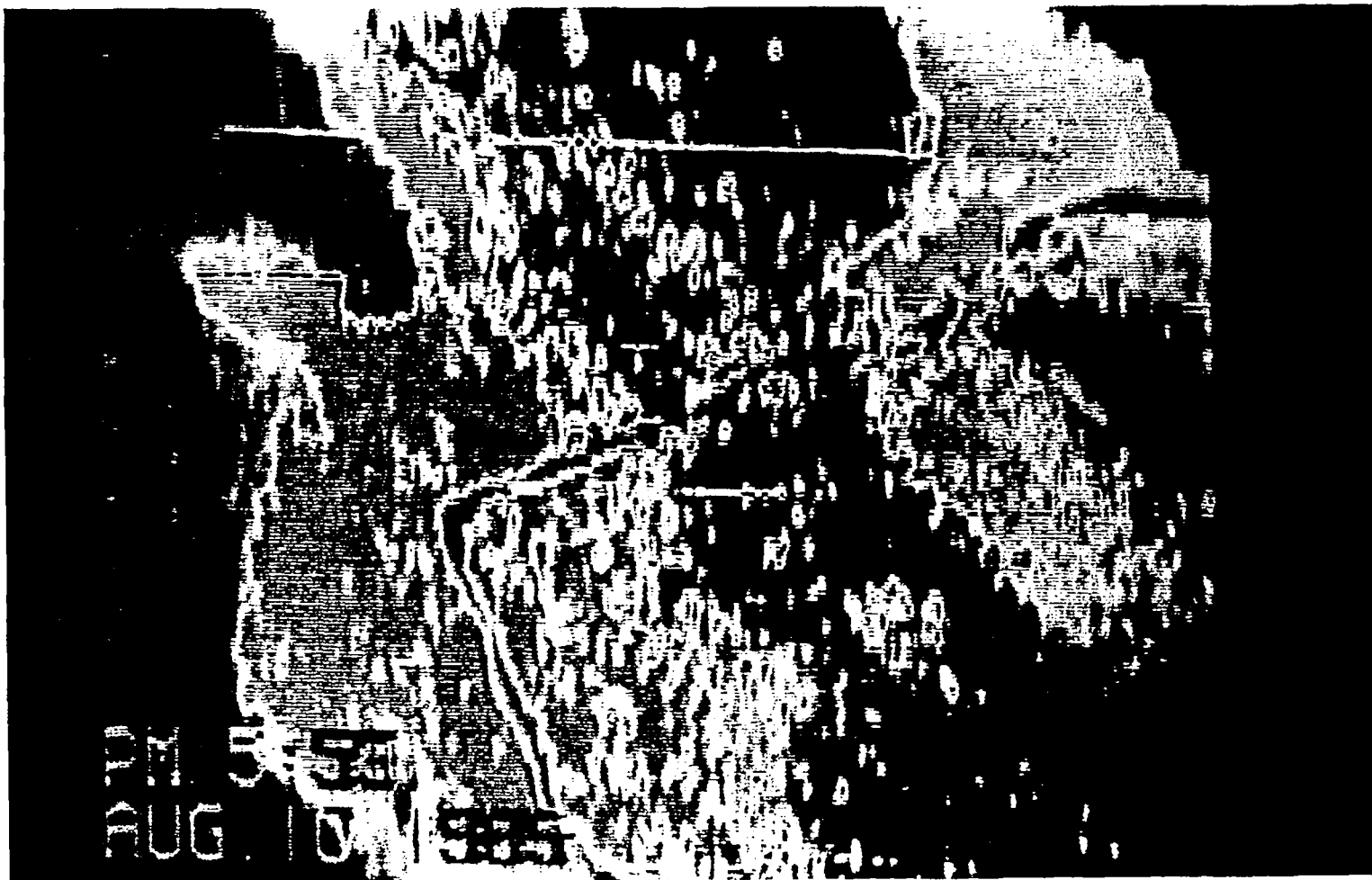


Figure VII G.4 False color infrared image of the Hill fire at 1753 LDT. See text for description of color scale.

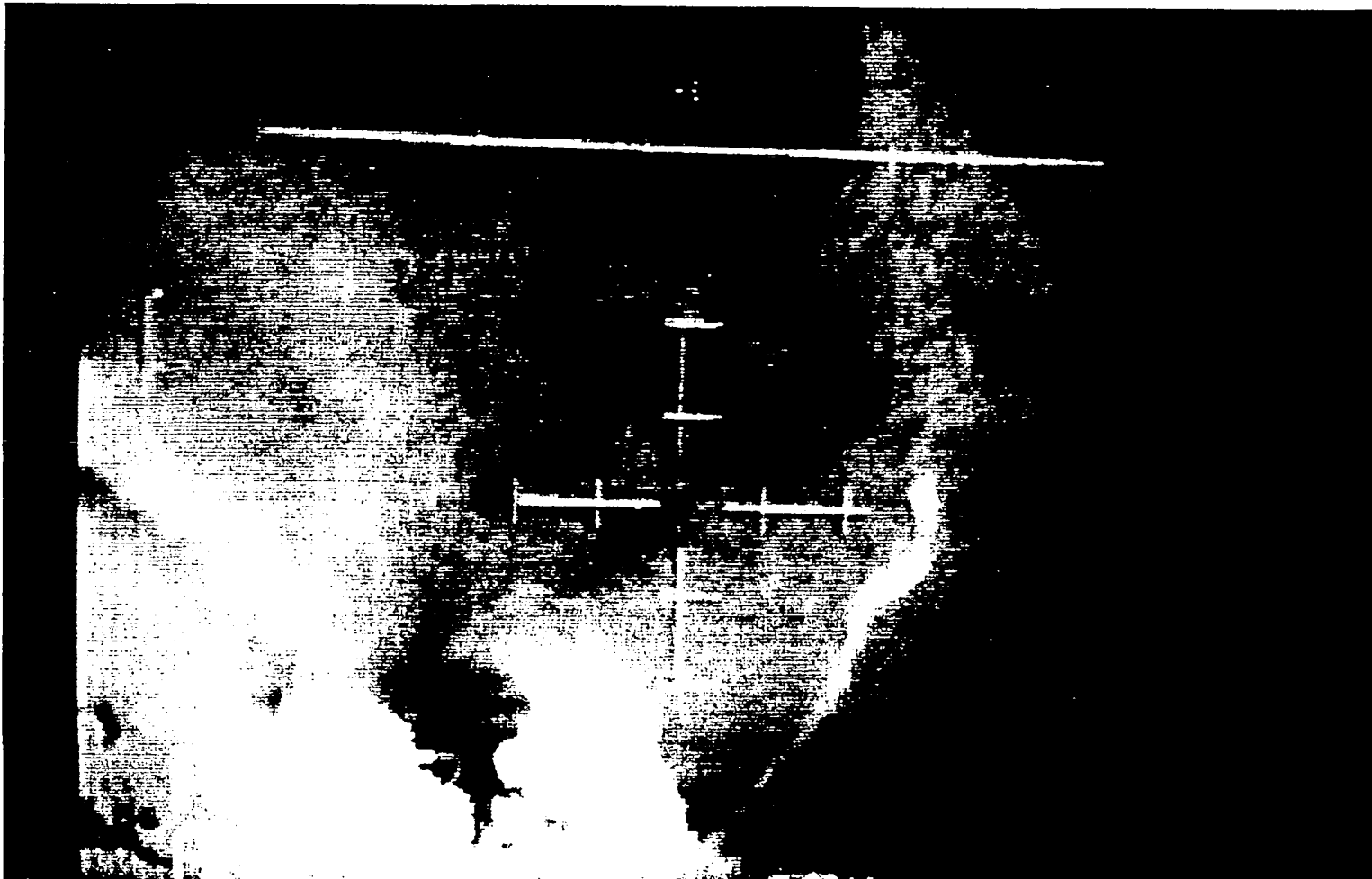


Figure VII G.5 Grey scale infrared image of the Wicksteed fire at 1527 LDT. Fire whirl is seen in the lower right.

(hot)? The answer is, of course, that they are reflecting the energy radiated by the fire. The fire is illuminating the extraordinarily large smoke particles lofted during intense combustion.

This phenomenon is nicely illustrated in Figure VII G.6 at 1515 LDT during the Wicksteed fire. Here the aircraft is over the fire site looking downwind. The smoke is strongly illuminated in grey scale and completely obscures the background. Similarly during very intense periods the sheer quantity of smoke degrades the image. In Figure VII G.7 we directly overfly the center of the fire looking down and see with this grey scale visible light video image the dark smokes from flaming and lighter smokes from smoldering combustion rising up from the Wicksteed fire. At 1635 LDT ignition is still continuing in a symmetrical spiral. The towering smoke column which rises past the cloud condensation level is off the image; thus this is only smoke in the field of view. When the now nadir pointing FLIR image is superimposed on the visible image (both images in false color) in Figure VII G.8, we see the expected symmetrical spiral of flaming (red) which were not visible in Figure VII G.7. The equally hot areas under thicker depths of (denser?) smoke are effectively obscured showing up as much cooler and poorly defined areas.

Summary

The excellent image quality of the AAQ-17 FLIR offers a potentially excellent tool for fire research both for mapping different phases and characteristics of the fire and for imaging fire related phenomena within the visually dense pall of smoke hiding these fires. Full utilization of the tool would require calibration and some means of quantitatively stepping sensor gain so that a broader thermal range would be imaged without the loss of invaluable detail of the non-combusting background.

We do note that sufficient super-micron smokes are lofted under some fire conditions to limit the quantitative utility of the device during these periods.

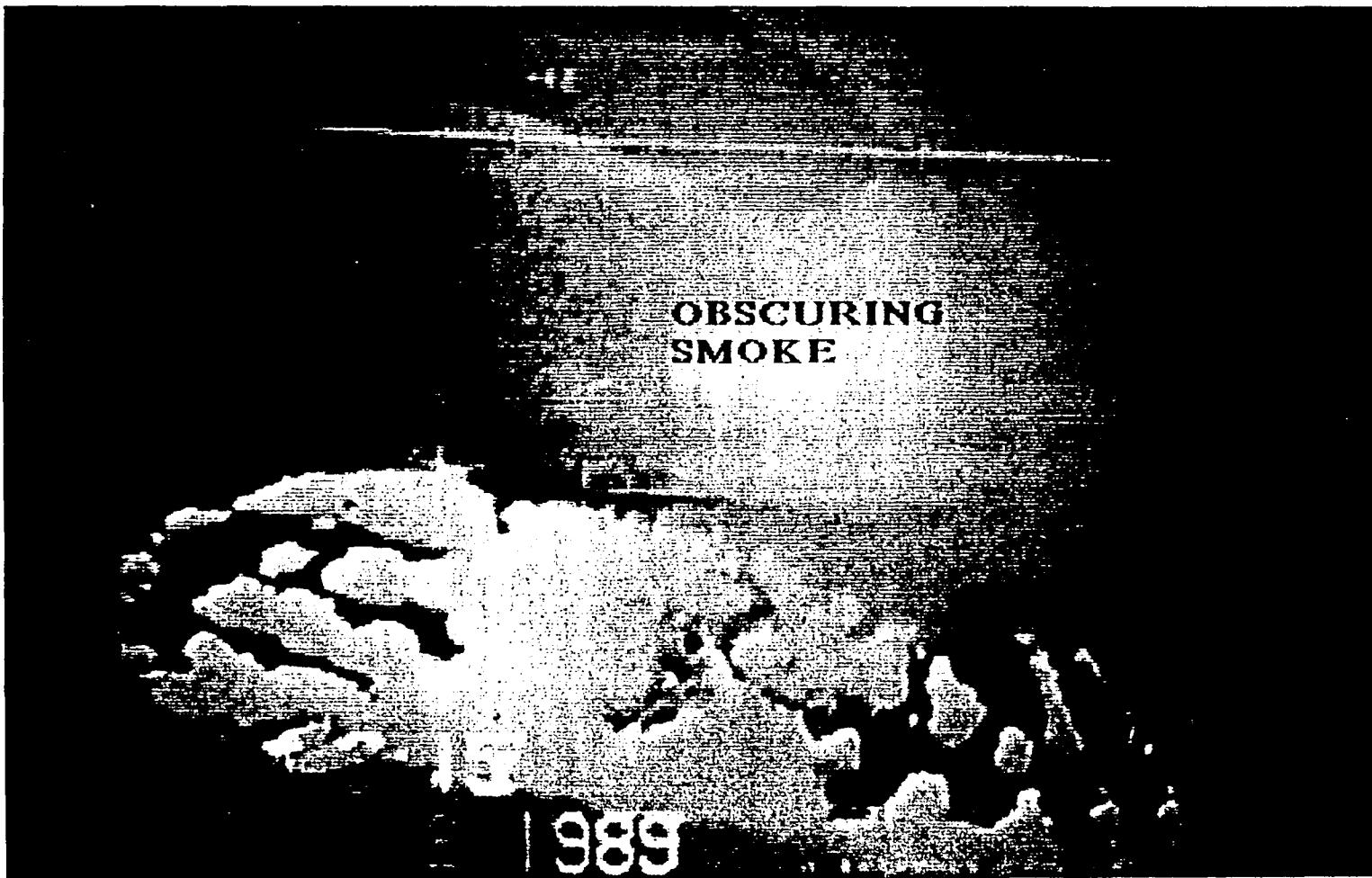


Figure VII G.6 Grey scale infrared image of the Wicksteed fire at 1515 LDT.



Figure VII G.7 Downward-looking video (visible wavelengths) image of the Wicksteed fire at 1635 LDT. The correct year should be 1989.



Figure VII G.8 False color video image of Wicksteed fire at 1635 LDT with superimposed false color infrared image. The correct year should be 1989.

LIDAR OBSERVATIONS

Introduction

The Hill and Wicksteed prescribed burns were the first field experiments for the UW/GTRI airborne lidar aboard the UW C-131A aircraft. A schematic representation of the lidar system along with a listing of specifications is given in Appendix B. The dual wavelength lidar (0.53 and 1.06 μm) was designed for air pollution research and is a sensitive detector of smoke particles. As operated in Canada, the lidar's spatial resolution at flight speeds was 7 m in the vertical and 8 m in the horizontal. The lidar was operated in the vertical mode (zenith pointing) with a maximum range, in this application, of 7.5 km above the aircraft's flight level.

As a corollary to its sensitivity to biomass smokes, the laser beams are significantly attenuated by the smokes. This is especially true when the lidar is operating at the shorter 0.53 μm wavelength according to Uthe (1982). Typically a lidar's quantitative measure of optical backscattering ends when the target's total optical depth, τ , exceeds about 3. In this application, that means if you cannot easily see the disk of the sun through the target cloud, you will not be able to recover lidar data at 0.53 μm through the depth of the cloud. Thus to image the smoke plume's complete vertical structure, cross-sections need to be made far enough downwind to be completely clear of the water droplets in the fire's capping cumulus cloud. Additionally, enough environmental mixing (dilution) must occur to meet the $\tau < 3$ requirement.

When these conditions were met, the lidar produced very useful data at both fires (as an aside, the potentially interesting lidar observations in optically thick clouds were largely lost because on the aircraft's negative g encounters the lidar shut itself off).

Results

Our preliminary analysis of the lidar observations of the fire smokes produced a number of surprises. A recurring characteristic is illustrated in Figure VII G.9 Here,

August 10, 1989

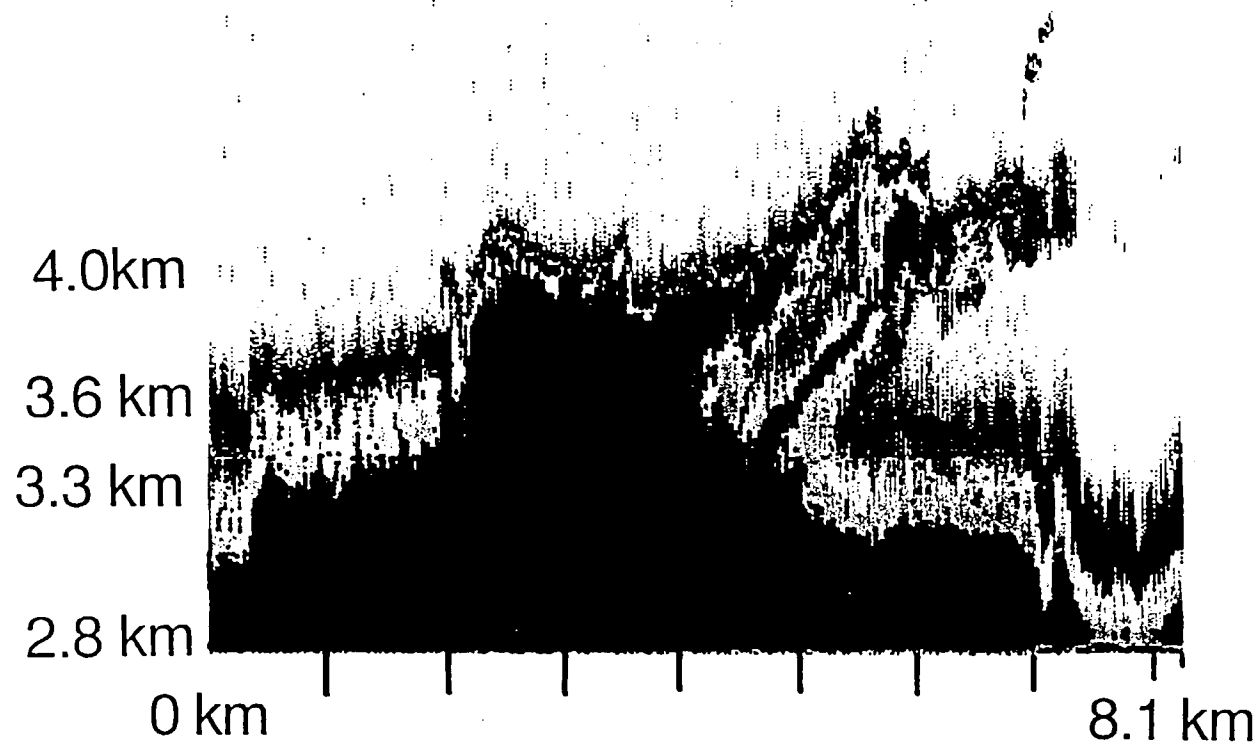


Figure VII G.9

Lidar image of a plume cross-section at the Hill fire starting at 1438 LDT.

despite the fact that the top of the fire capping cumulus is ~7 km, essentially all of the smoke detraining from the cumulus is being released within a narrow range of altitudes. This phenomenon was most apparent at the Hill fire where essentially all of the smoke was initially ingested by the capping cumulus. The sample in Figure VII G.9 was taken perpendicular to the plume axis with the aircraft flying near the base of the plume. Black represents the optically most dense portion of the smoke plume. The color progression then moves through red, yellow, green and blue before reaching white which represents molecular scattering. The "jets" of smoke between 4 and 7 km is a common feature of both fires. The consequences of such "jets" is seen in Figure VII G.10 where 10 minutes earlier, but further downwind, we have another cross-section. The center axis of the plume is the center of the figure. The elevated wings are smoke released from the capping cumulus at various altitudes. Again the observation of interest is that comparatively little smoke was detrained from the cumulus much above cloud base, and the higher smokes which were detrained were sharply limited in altitude (although the altitude varies).

Figure VII G.11, from the Wicksteed fire, shows a view along the plume axis of a similar feature. The capping cloud top is ranging from 6 to 7 km, but the highest smoke detraining is at ~4 km. This detrained smoke at 4 km is a small fraction of the smoke being released (note that the capping cumulus at Wicksteed did not always ingest all of the smoke column; some of the smoke stabilized near cloud base and proceeded downwind without cloud scavenging or processing).

Summary

The use of lidar has interfered with a number of cherished conceptual views of how smoke exits a fire capping cumulus. It does not detrain like ice crystals at the top of anvil cumulus (if the mechanism for forming an anvil is not present). Neither does the smoke detrain in some uniform haze on the downwind side. Rather most of the smoke in these fires is detrained within a kilometer above cloud base. Smoke detraining higher up usually

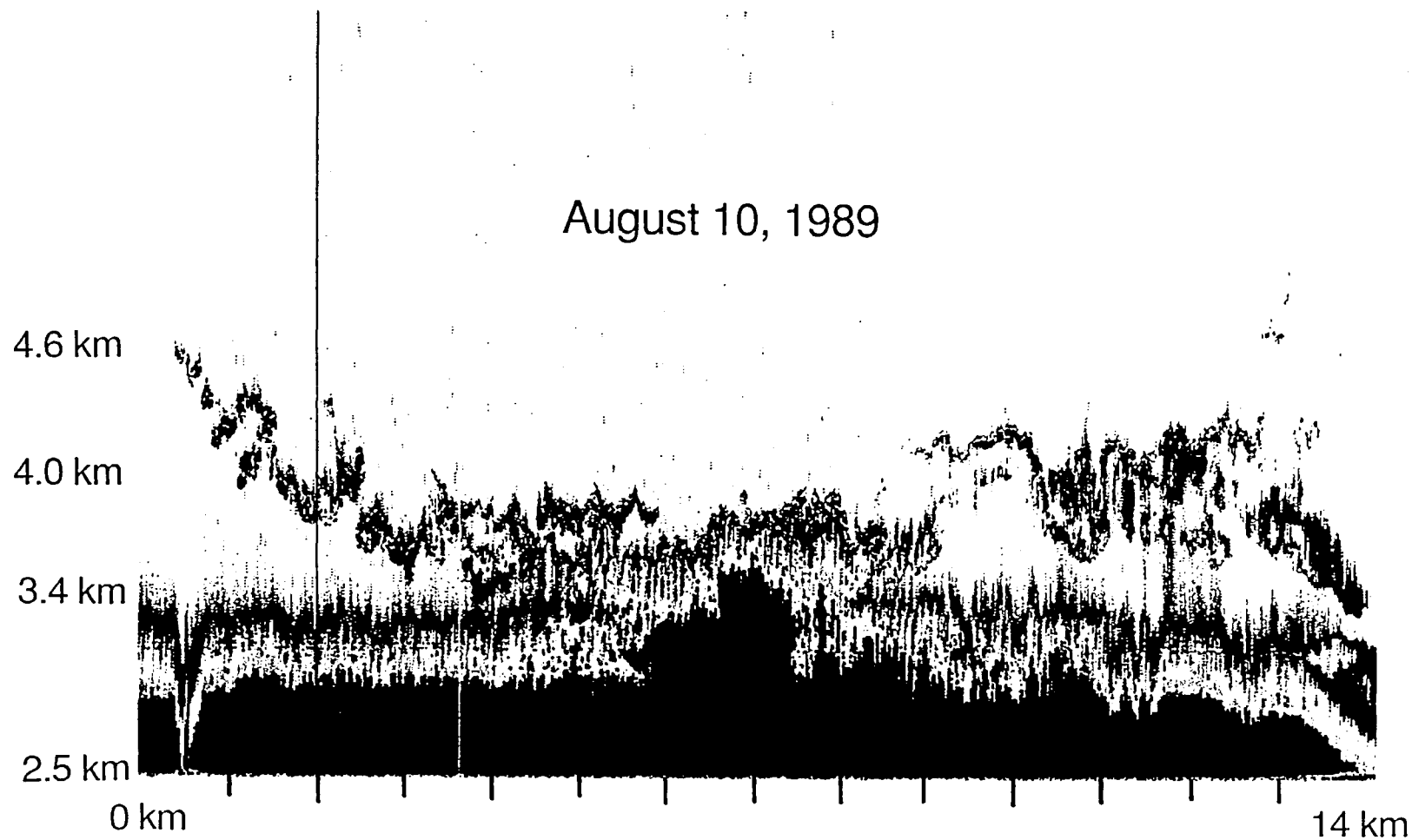


Figure VII G.10 Lidar image of a plume cross-section at the Hill fire starting at 1426 LDT. The odd feature at 0.5 km is an abrupt turn of the aircraft platform.

August 12, 1989

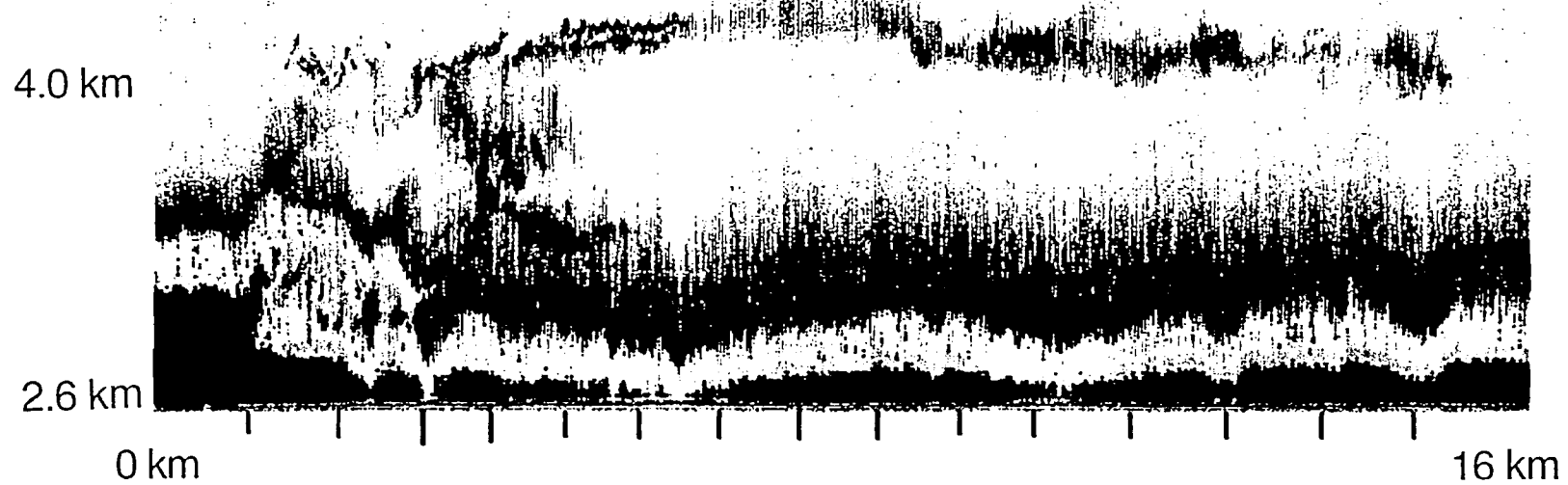


Figure VII G.11 Lidar image taken along the axis of the plume at the Wicksteed fire.
The furthest distances downwind are at the extreme right.

did so at relatively discrete altitudes, although the altitude seems to be related to cumulus dynamics rather than the presence of obvious stable layers in the free atmosphere.

Thus our lidar observations seem to raise more questions - perhaps important ones - about the injection height of smokes from large fires.

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APPENDIX

THE UNIVERSITY OF WASHINGTON'S CONVAIR C-131A RESEARCH AIRCRAFT

All of the airborne measurements needed for this study can be obtained aboard the University of Washington's C-131A aircraft.

General Description of Airborne Facilities

The Convair C-131A is a twin-engine, propeller driven aircraft that is large enough to carry a large instrumentation payload plus a crew of up to eight persons.

The layout of the work stations and major instrumentation units on the aircraft is shown in Figure A.1.

Details on the instrumentation presently aboard the aircraft are given in Table A.1, where they are grouped under the following headings: navigational and flight characteristics, general meteorological, cloud physics, aerosol, cloud and atmospheric chemistry, remote sensing, and data processing and display. The interrelationships between the scientific crew, the various measurement systems, and the data display and recording systems, are shown schematically in Figure A.2.

Data Recording and Data Display

Data from the various instruments aboard the aircraft are digitized and distributed to both a microcomputer for on-board display and an independent digital tape cartridge recording system for post-flight analysis. The flight scientists, systems engineer, cloud and aerosol scientist and atmospheric chemist stations each have terminals and color graphics displays to access data from the computer via a multi-user operating system (see Figure A.2). Software is available to display up to twenty measured parameters, as well as particle and droplet spectra, aircraft position plots, histograms of selected parameters and radar/lidar reflectivity profiles. Fast data-rate instrumentation (such as the lidar, 35 GHz radar and cloud absorption radiometer), employ separate 9-track magnetic tape recording systems. Time synchronization is assured by the use of a clock signal common to all the measuring systems.

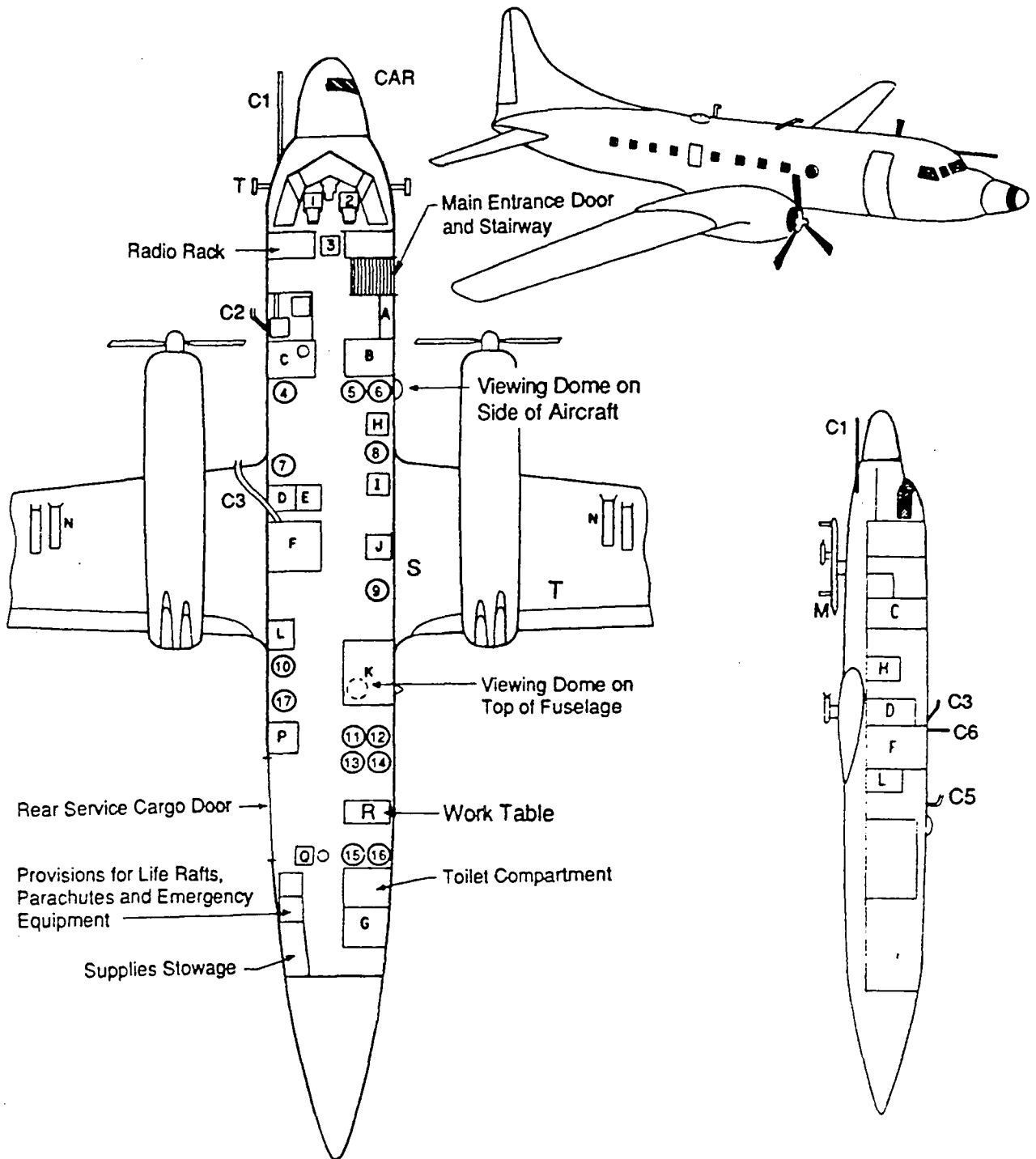


Figure A.1 Layout of work stations and major research instrumentation units aboard the University of Washington's Convair C-131A research aircraft. (See following page for key to letters and numbers.)

KEY TO LETTERS AND NUMBERS IN FIGURE A-1

1. Pilot
2. Co-Pilot
3. Flight Scientist or Meteorologist
4. Aerosol Scientist
5. Flight Scientist or Meteorologist
6. Flight Scientist or Meteorologist
7. Chemist
8. Flight Engineer
9. Cloud Absorption Radiometer (CAR) Operator
10. Cloud Condensation Nucleus (CCN) Counter Operator
- 11-12. Landing, Take Off and Crew Rest Stations
13. Operator for Lidar and/or Counterflow Virtual Impactor (CVI)

Locations of Major Research Instrumentation Units

- A. Inverters and power distribution.
- B. Scientific situation display including digital and graphical monitors, analog and digital hard copies, radio and telecommunications.
- C. Primary aerosol characterization system.
 - C1. Inlet supplies the grab sampler.
 - C2. Inlet supplies the heated plenum and Hi Vol sample ports.
 - C3. Inlet supplies the 1.5 m³ bag sampler and the trace gas detection system.
 - C4. Inlet for 7 m long light extinction and light scattering cells.
 - C5. Inlet for CVI.
 - C6. Inlet for cloud water sampler.
- D. Trace gas system for DMS, NO, NO₂, HNO₃, PAN, SO₂, O₃, CO and CO₂.
- E. Cloud water and wet chemistry system for hydrometeor inorganic and some organic ions, and aqueous H₂O₂.
- F. Enclosed 1.5 m³ bag sampler and aerosol filter system.
- G. Vacuum pump cabinet.
- H. Data computer and recording system.
- I. Controls for meteorological sensors.
- J. Cloud absorption radiometer controls and data recorder.
- K. Sensor for DMS and hemispheric viewing dome.
- L. Cloud condensation nucleus spectrometer.

- M. Pod (located on aircraft belly under position 3) liquid water sensors (J-W and King).
UW ice particle counter and PMS FSSP probe.
- N. Under wing mounts for 1 and 2-D PMS cloud and precipitation probes.
- O. Visible and UV net radiometers on the top and bottom of fuselage.
Sea surface temperature sensor on bottom of fuselage.
- P. Lidar data system and CVI controls.
- Q. Nd-YAG Lidar
- R. 35 GHz ($\lambda=0.86$ cm) Radar
- S. Antennas for 35 GHz radar (upward and downward looking on top and bottom of wing)
- T. Ophir IR optical hygrometer

TABLE A.1

TABLE A.1. INSTRUMENTATION ABOARD THE UNIVERSITY OF WASHINGTON'S AIRCRAFT

Parameter	Instrument Type	Manufacturer	Range (and error)
(a) <u>Navigational and Flight Characteristics</u>			
Latitude and longitude, ground speed and horizontal winds	VLF: Omega navigator	Litton LTN-3000	0 to 300 m s ⁻¹ (± 1 m s ⁻¹ groundspeed and ± 1° drift angle)
True airspeed	Variable capacitance	Rosemount Model 831 BA	0 to 250 m s ⁻¹ ($< 0.2\%$)
Heading	Gyrocompass	King KCS-55A	0 to 360° (± 0.5°)
Pressure altitude	Variable capacitance	Rosemount Model 830 BA	150 to 1100 mb ($< 0.2\%$)
Altitude above terrain	Radar altimeter	AN/APN22	0 to 6 km ($< 5\%$)
Aircraft position and course plotter	Derived from VLF/OMEGA	In-house	180 km (1 km)
Angle of attack	Potentiometer	Rosemount Model 861	± 23° ($< 0.5\%$)
Rate of climb	Variometer	Ball Engineering	± 12 m s ⁻¹
(b) <u>General Meteorological</u>			
Total air temperature	Platinum wire resistance	Rosemount Model 102CY2CG + 414 L Bridge	-60 to 40°C ($< 0.1^\circ\text{C}$)
Static air temperature	Reverse-flow thermometer	In-house	-60 to 40°C ($< 0.5^\circ\text{C}$)

TABLE A.1. (Continued)

Parameter	Instrument Type	Manufacturer	Range (and error)
(b) <u>General Meteorological (Continued)</u>			
Dew point	Dew condensation	Cambridge Systems Model TH73-244	-40 to 40°C ($< 1^\circ\text{C}$)
Absolute humidity	IR optical hygrometer	Ophir Corporation Model IR-2000	0 to 10 gm^{-3} ($\sim 5\%$)
Air turbulence	Differential	Meteorology Research, Inc. Model 1120	0 to 10 $\text{cm}^{2/3} \text{s}^{-1}$ ($< 10\%$)
Pyranometer(s) (one downward and one upward viewing)	Eppley thermopile	Eppley Laboratory, Inc. Model PSP	0 to 1400 W m^{-2} ($\sim 1\%$)
Sea surface temperature	IR radiometer	Barnes PRT-5	variable
Ultraviolet radiation	Barrier-layer photoelectric cell	Eppley Laboratory, Inc. Model 14042	0 - 70 $\text{J m}^{-2} \text{s}^{-1}$ ($< 5\%$)
Photographs	35mm time-lapse camera	Automax Model GS-2D-111	1 s to 10 min
Video tape	Forward looking video camera + time code	General Electric	VHS format
Video tape	Upward and downward looking video camera	NEC	S-VHS format
(c) <u>Cloud Physics</u>			
Liquid water content	Hot wire resistance	Johnson-Williams	0 to 2 and 0 to 6 g m^{-3}
Liquid water content	Hot wire resistance	King/PMS	0 to 5 g m^{-3}

TABLE A.1. (Continued)

Parameter	Instrument Type	Manufacturer	Range (and error)
(c) <u>Cloud Physics (Continued)</u>			
Size spectrum cloud particles	Forward lightscattering	Particle Measuring Systems Model FSSP	2 to 47 μm^*
Size spectrum cloud particles	Diode occultation	Particle Measuring Systems Model OAP-200X	20 to 300 μm^*
Size spectrum of precipitation particles	Diode occultation	Particle Measuring Systems Model OAP-200Y	300 to 4500 μm^*
Images of cloud particles	Diode occultation imaging	Particle Measuring Systems Model OAP-2D-C	Resolution 25 μm^*
Images of precipitation particles	Diode imaging	Particle Measuring Systems Model OAP-2D-P	Resolution 200 μm^*
Ice particle concentrations	Optical polarization technique	In-house	0 to 1000 l-1 detects particles ($> 50 \mu\text{m}$)*
(d) <u>Aerosol</u>			
Number concentrations of particles	Light transmission	General Electric Model CNC II	10^2 to 10^6 cm^{-3} (particles $> 0.005 \mu\text{m}$)*
Cloud condensation nucleus spectrometer	Vertical-plate continuous flow	In-house	4 selectable supersaturations between 0.2 and 2%.
Mass concentration particles	Electrostatic deposition onto matched oscillators	Thermal Systems, Inc. Model 3205	0.1 to 3000 $\mu\text{g m}^{-3}$ ($< 0.2 \mu\text{g m}^{-3}$)
Size spectrum of particles	Electric aerosol analyzer	Thermal Systems, Inc. Model 3030	0.0032 to 1.0 μm^*
Size spectrum of particles	90° lightscattering	Particle Measuring System (LAS-200)	0.5 to 11 μm^*

* All particle sizes refer to maximum particle dimensions.

* All particle sizes refer to maximum particle dimensions

TABLE A.1. (Continued)

Parameter	Instrument Type	Manufacturer	Range (and error)
(d) <u>Aerosol (Continued)</u>			
Size spectrum of particles	Forward lightscattering	Royco 245 (In-house modified)	1.5 to 40 μm^*
Size spectrum of particles	Diffusion battery	Thermal Systems, Inc. Model 3040 with in-house automatic valves and sequencing	0.01 to 0.2 μm^*
Size spectrum of particles	35 - 120° lightscattering	Particle Measuring Systems Model ASASP-X	0.09 to 3.0 μm ($< 0.007 \mu\text{m}$) [*]
Size spectrum of particles	Forward lightscattering	Particle Measuring Systems Model FSSP	2 to 47 μm^*
Size-segregated concentrations of particles	Cascade impactor	Sierra Instruments Inc.	0.1 to 3 μm^* (6 size fractions)
Light-scattering coefficient	Integrating nephelometer	Meteorology Research, Inc. Model 1567 (modified for increased stability and better response time)	$1.0 \times 10^{-6} \text{ m}^{-1}$ to $2.5 \times 10^{-3} \text{ m}^{-1}$
Light-extinction coefficient	Optical extinction cell (2 m path length)	Waggoner Electronics	5×10^{-5} to 10^{-2} m^{-1}
(e) <u>Cloud and Atmospheric Chemistry</u>			
Cloud water samples	Impaction on slotted rods	In-house modification of ASRC sampler	Bulk cloud water collection efficiency ~ 40% based on analysis of in-house flight data
Cloud droplet nucleus collector	Counterflow virtual impactor	In-house	Drops $> 7 \mu\text{m}$ diameter

* All particle sizes refer to maximum particle dimensions

TABLE A.1. (Continued)

Parameter	Instrument Type	Manufacturer	Range (and error)
e) <u>Cloud and Atmospheric Chemistry (Continued)</u>			
Particulate sulfur $\text{SO}_4^{=}$, NO_3^- , Cl^- , Na^+ , K^+ , NH_4^+	Teflon filters CSI & XRF spectroscopy and Dionex ion exchange chromatography	In-house	0.1 to 50 $\mu\text{g m}^{-3}$ (for 500 liter air sample)
SO_2	Impregnated filters	In-house	≥ 20 pptv (for 5 m^3 air sample)
SO_2	Pulsed fluorescence	Teco SP43 (modified in-house)	1.0 ppb to 5 ppm
Ozone	Chemiluminescence (C_2H_4)	Monitor Labs Model 8410 A	0 to 5 ppm (< 7 ppb)
NO , NO_2 , NO_x	Chemiluminescence (O_3)	Modified Monitor Labs Model 8840	0 to 5 ppm (~ 1 ppb)
HNO_3	Nylon filters with teflon pre-filter followed by ion chromatography and/or tungstic acid denuder tubes followed by chemiluminescent detection	Dionex/Monitor Labs	Variable
CO	Correlation spectrometer	Teco Model 48	0 - 50 ppm (~ 0.1 ppm)
CO_2	Correlation spectrometer	Customized Teco Model 41H	0 - 1000 ppm (~ 4 ppm)
DMS	Absorption on gold wires, followed by gas chromatography with flame photometric detection	In-house	> 1 pptv ($\pm 10\%$)

(f) Remote Sensing

Absorption and scattering of solar radiation by clouds and aerosols	Scanning cloud absorption radiometer	NASA-Goddard/ U of Washington	13 wavelengths between 0.5 and and 2.3 μm
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TABLE A.1. (Continued)

Parameter	Instrument Type	Manufacturer	Range (and error)
(f) <u>Remote Sensing (Continued)</u>			
Radar reflectivity	Pulsed 35 GHz ($\lambda = 0.86$ cm) radar	In-house	Upward and downward pointing (600 m to 20 km)
Optical backscatter	Nd-YAG lidar (dual- wavelength, polarization diversity)	Georgia Tech & U. of Wash.	0-15 km (7.5m resolution)
(g) <u>Data Processing and Display</u>			
Time	Time code generator	Systron Donner Model 8220	h, min, s ($1:10^5$)
Time	Radio UW	Gertsch RHF 1	--
Ground communication	FM transceiver	Motorola	200 km
In-flight data processing	Microcomputer	In-house, based on Motorola MVME-133A technology	--
In flight color graphics	Microcomputer	In-House, based on Motorola MVME-133A technology	--
Recording (digital)	Microcomputer-directed cartridge recorder	In-house, based on 3M technology	--
Recording (digital)	Floppy disk	---	--
Recording (analog voice transcription)	Cassette recorder	Radio Shack	--
Digital printout	Impact printer	Mannesman Tally MT 160	
Analog strip charts	6-channel high-speed ink recorder	Brush Model 260	--

APPENDIX B

THE UNIVERSITY OF WASHINGTON-GEORGIA TECH
AIRBORNE LIDAR SYSTEM

Specifications

A) Laser

Type: Neodymium-doped Yttrium Aluminum Garnet (Nd-YAG)
Wavelengths: 1.064 and 0.532 μm
Energies: 70 and 45 mJ
Pulse width: 20 ns
Beam divergence: 1 mrad

B) Telescope

Type: Cassegrainian
Diameter: 0.356m (14 in)

C) Detection

Polarizing filters: selectable for parallel and perpendicular polarizations
Detectors: 1.064 μm
Type: Silicon Avalanche Photodiode
0.532 μm
Type: Photomultiplier tube

D) Data acquisition/control system

Data input

Type: CAMAC crate
Manufacturer: DSP Technologies, Inc.
Digitization rate: 50 ns
Shot rate: 10 Hz

Control/display computer: 20 MHz 80386 based
IBM PC/AT compatible

Data display: VGA monitor (640 x 480 pixels)

Data storage: 80 megabyte hard disk, floppy disks, or
2.2 gigabyte mini-video cassettes

A schematic of the lidar system is shown in Fig. B.1

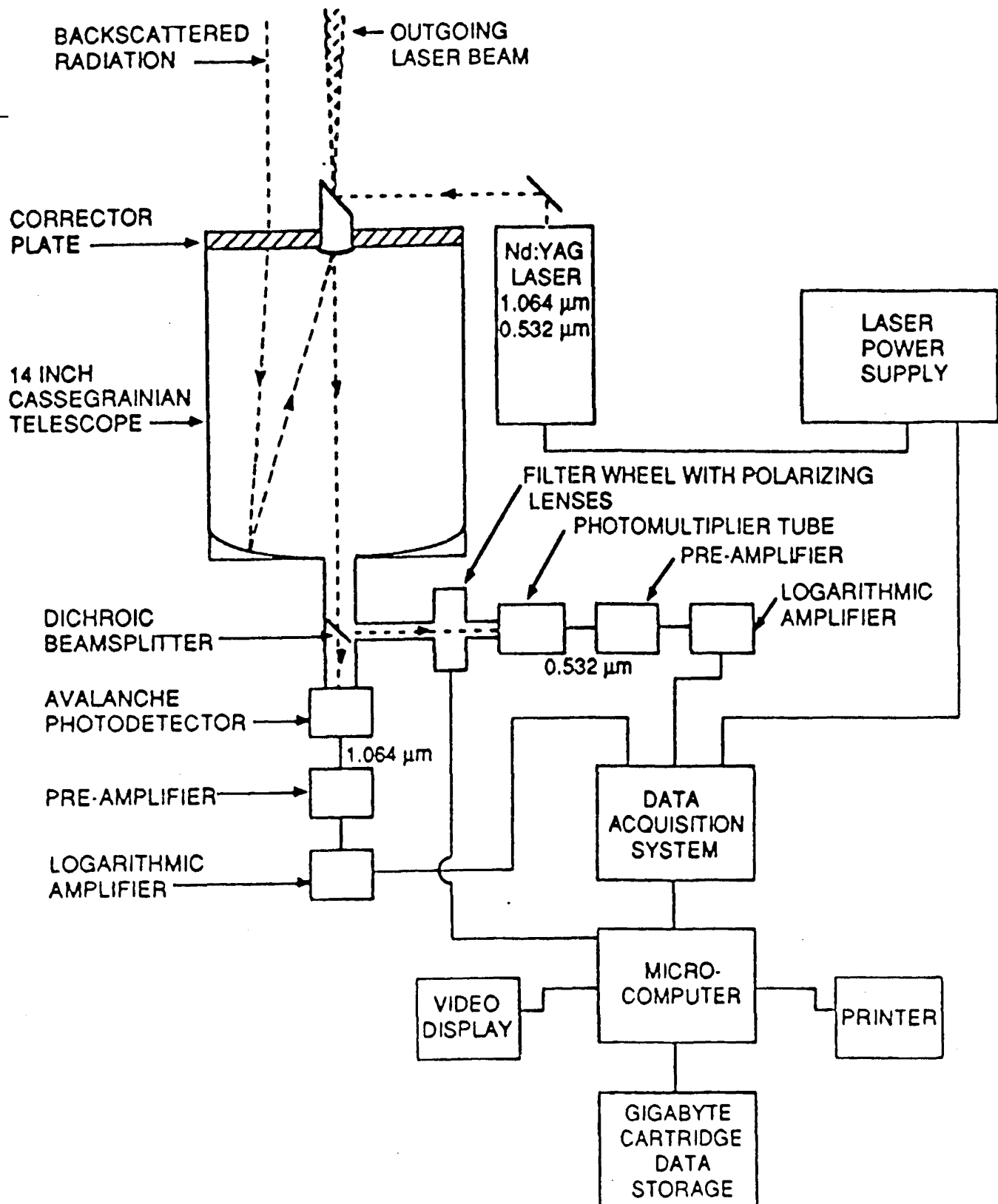


Figure 1. Schematic of the University of Washington-Georgia Tech Lidar System